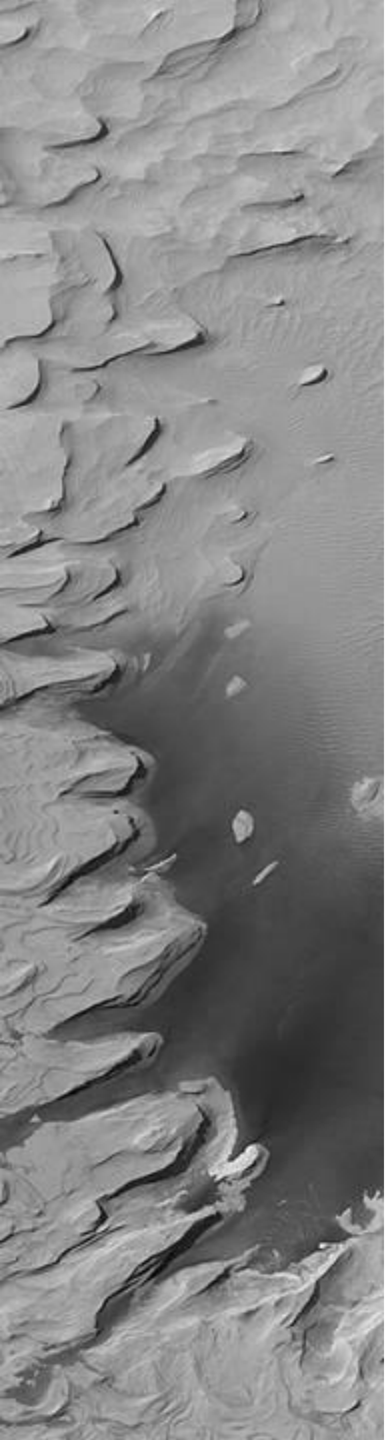

# From Sojourner to Curiosity, The Guidance, Navigation, and Control Challenges of Landing on Mars


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*Jet Propulsion Laboratory, California Institute of Technology*


**JCATI 2017 Symposium**

**Washington State University**

Seattle, Washington

4 April, 2017

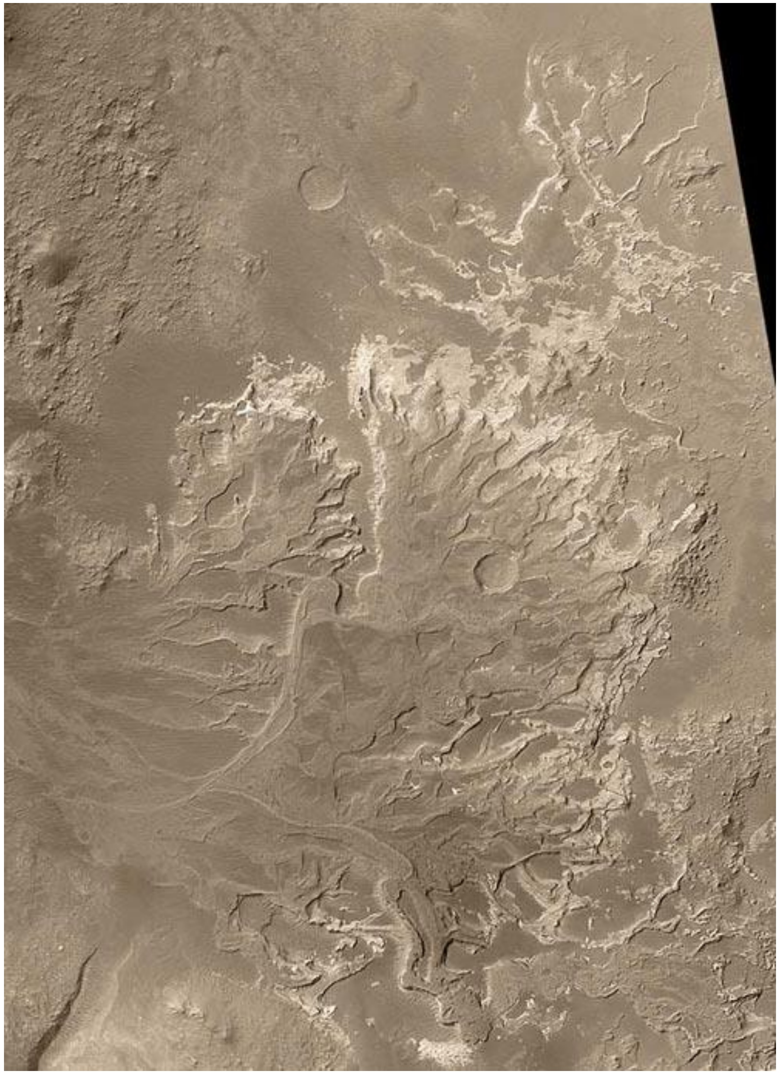
# Why Mars?

- There is scientific evidence that Mars was once a warm and wet planet like Earth and, therefore, it might have had the conditions necessary for the origin of life.

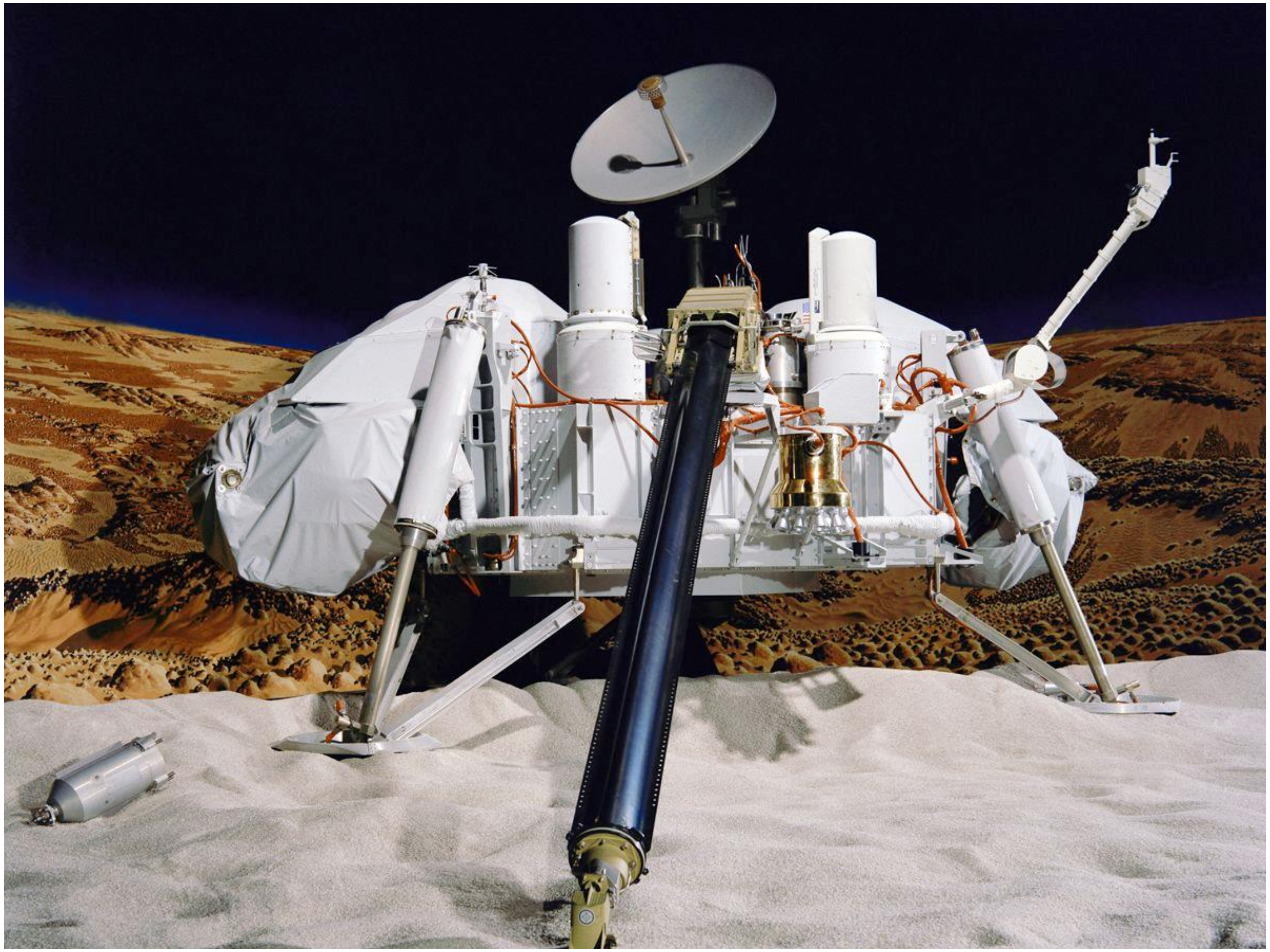
- ***Question: Was there life on Mars in the distant past or present?***

- The main objective of Mars exploration since Mars Pathfinder has been to determine if the basic elements needed for the origin of life were ever present in Mars.

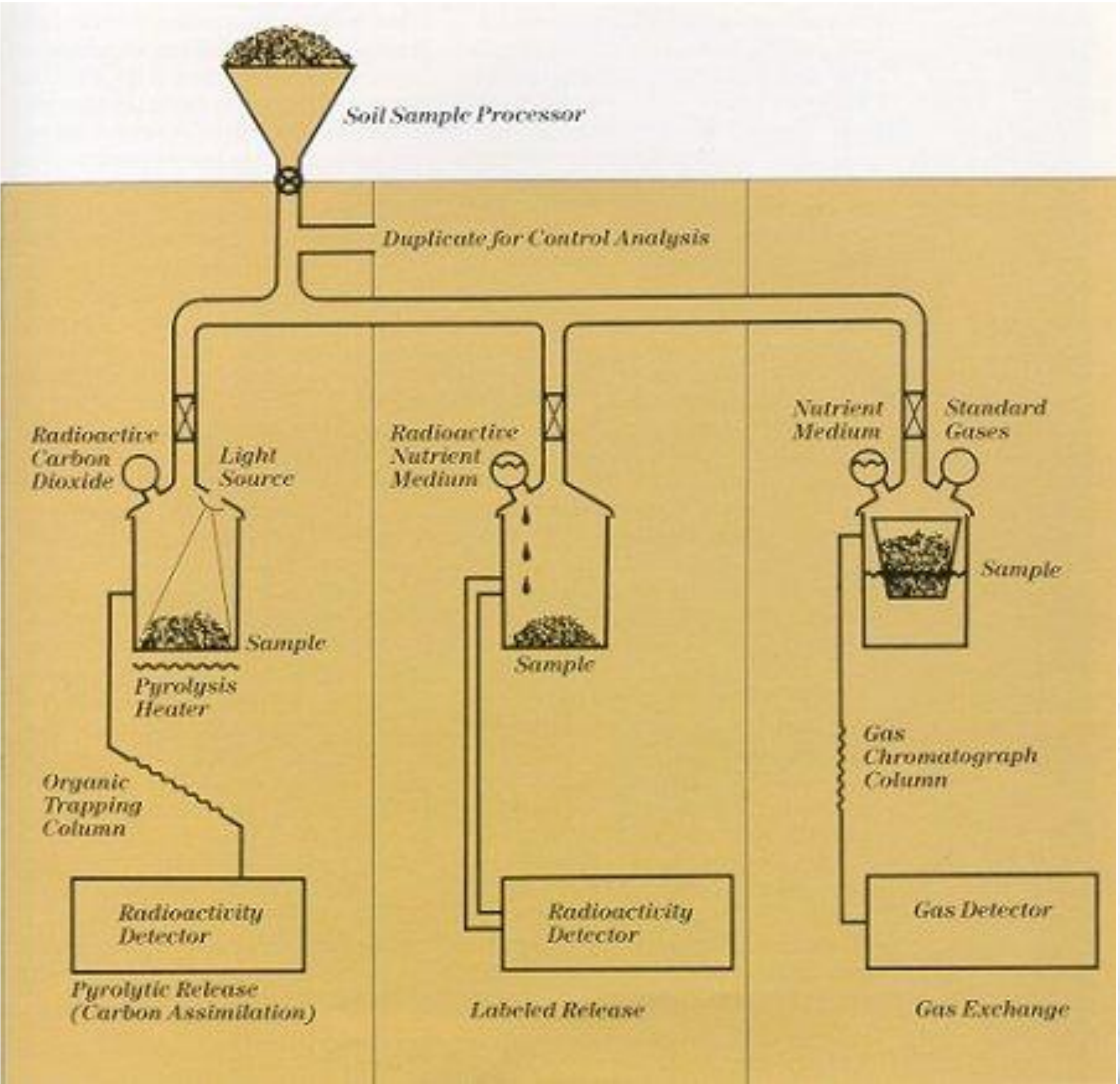
- Future missions will attempt to find direct evidence of past or present life.

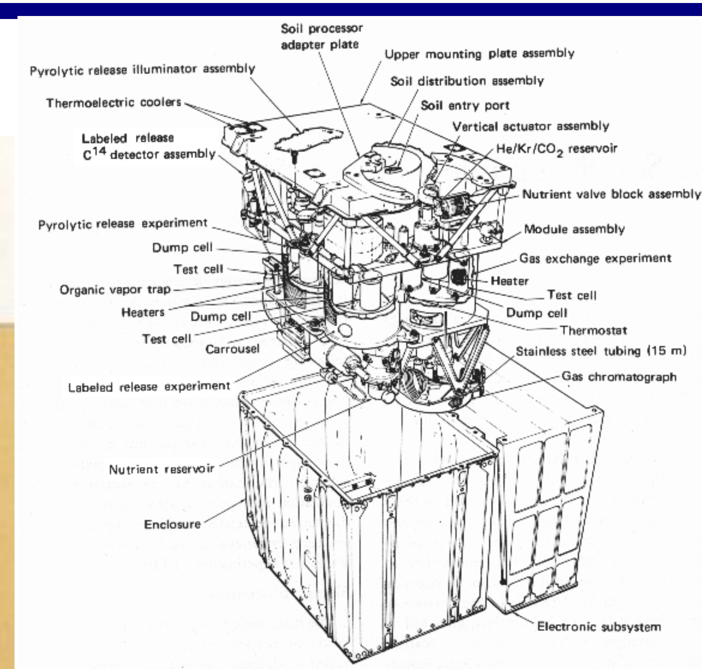


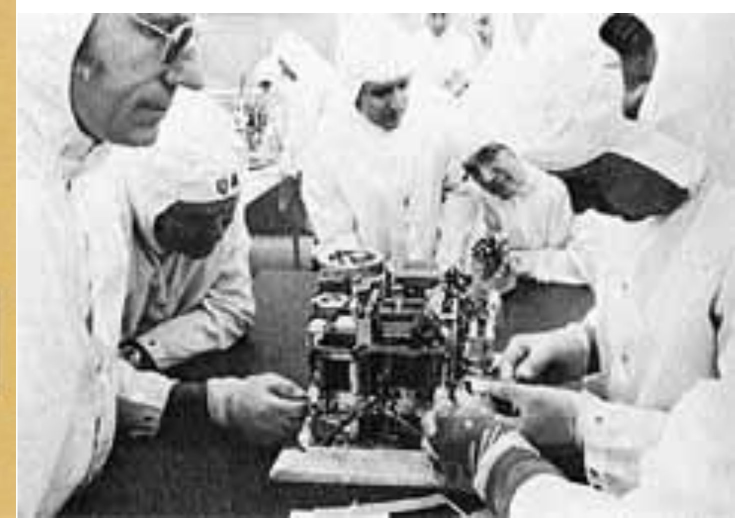
# Viking I & II (1976)



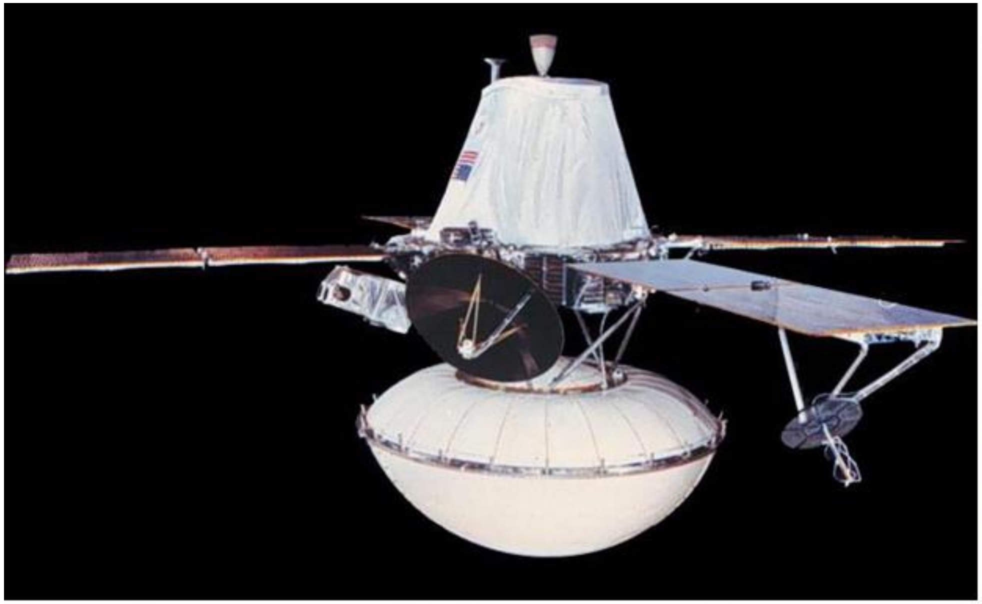
# Viking Biological Instruments

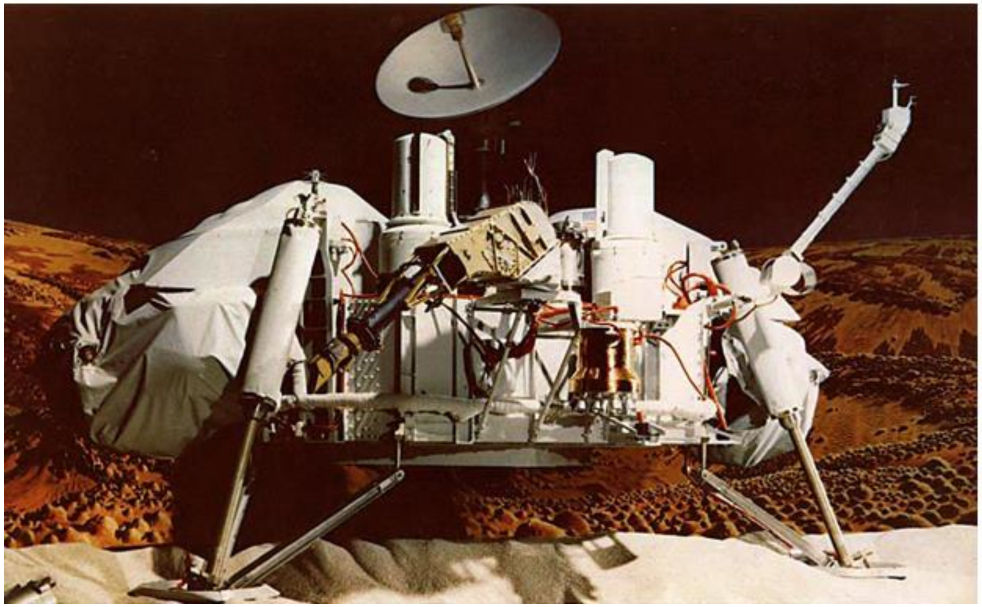


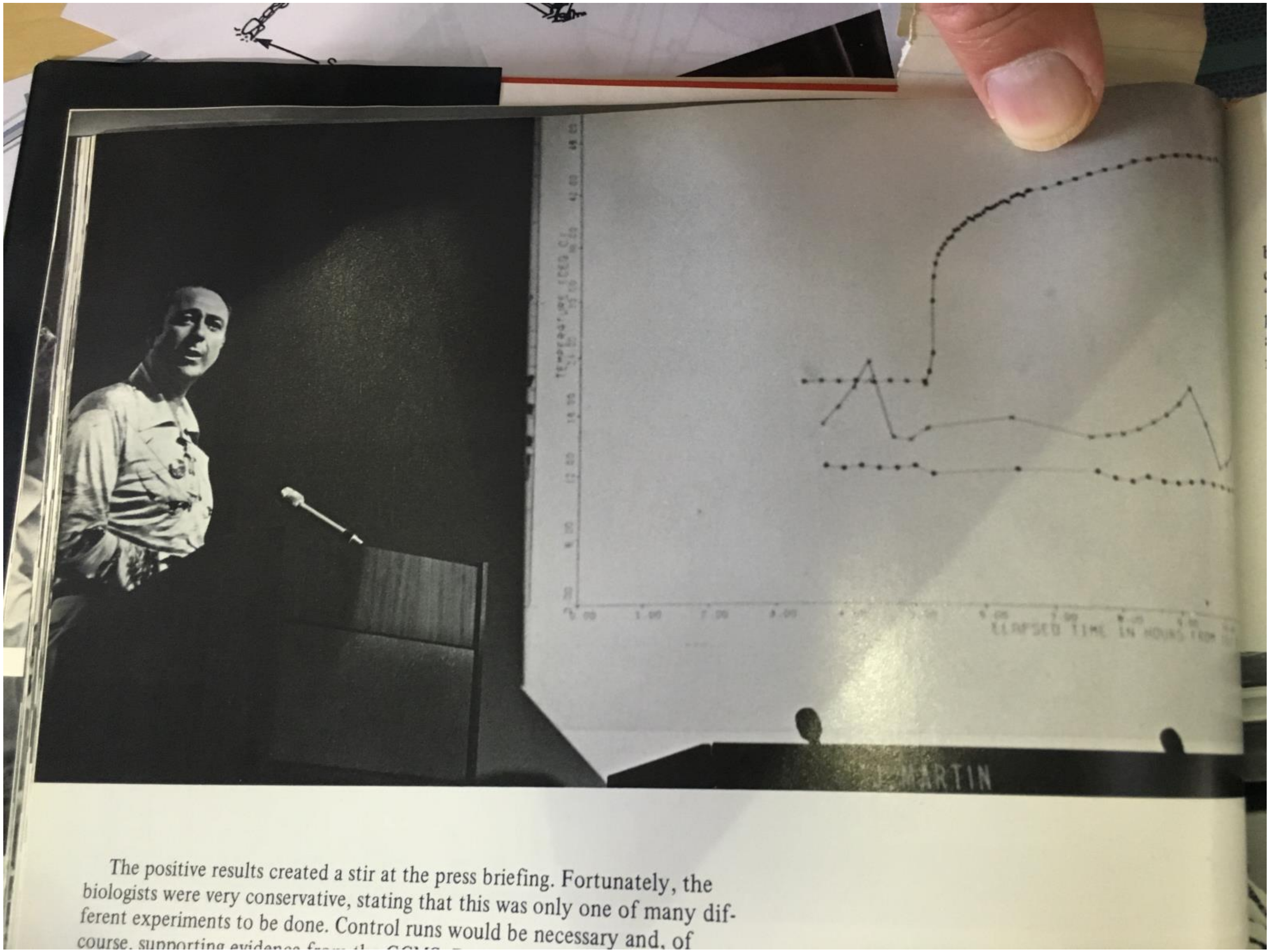
# Viking (1976)



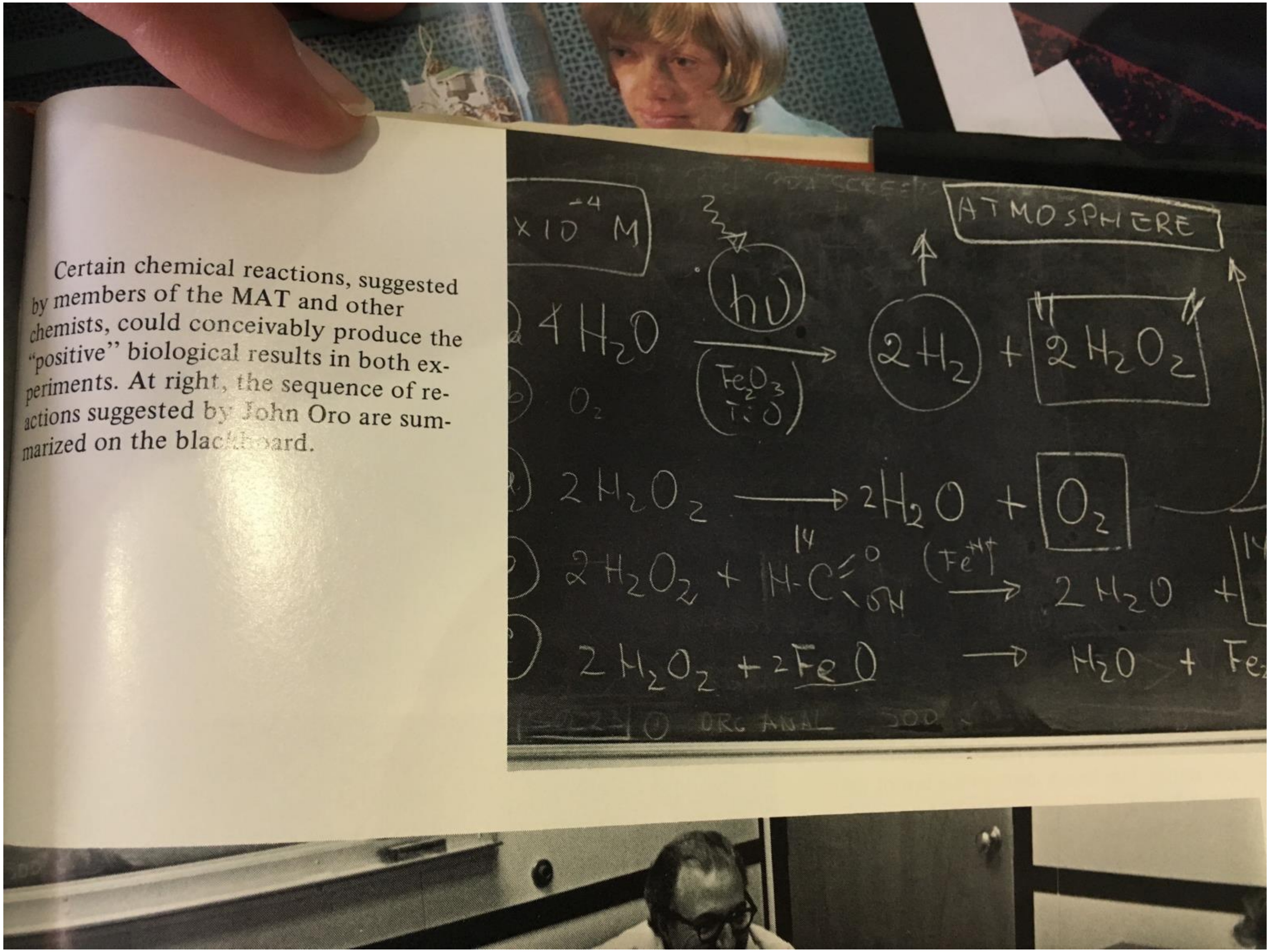


# Viking I and Big Joe

# Labeled Release Experiment: The Results



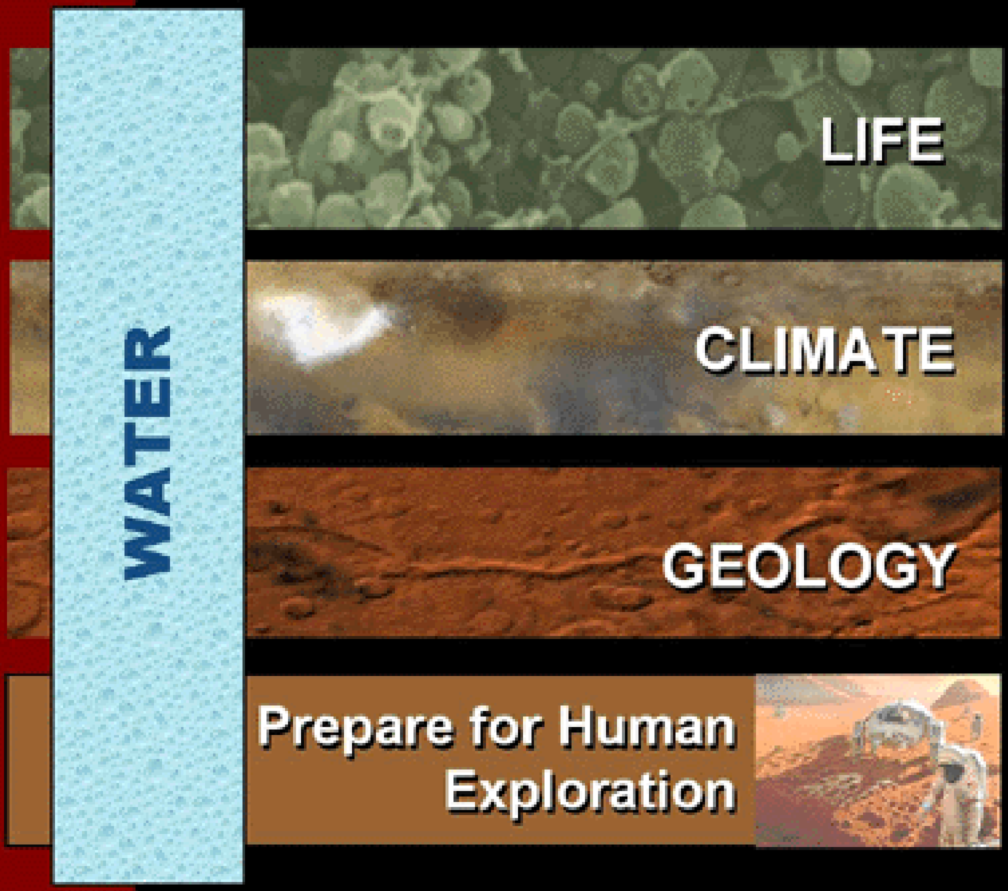
# Labeled Release Experiment: No Life!!




R.I.P.
Mars Exploration
1964-1976

# The Mars Science Strategy: "Follow the Water"

- When was it present on the surface?
- How much and where?
- Where did it go, leaving behind the features evident on the surface Mars?
- Did it persist long enough for life to have developed?




Understand the potential for life elsewhere in the Universe

Characterize the present and past climate and climate processes

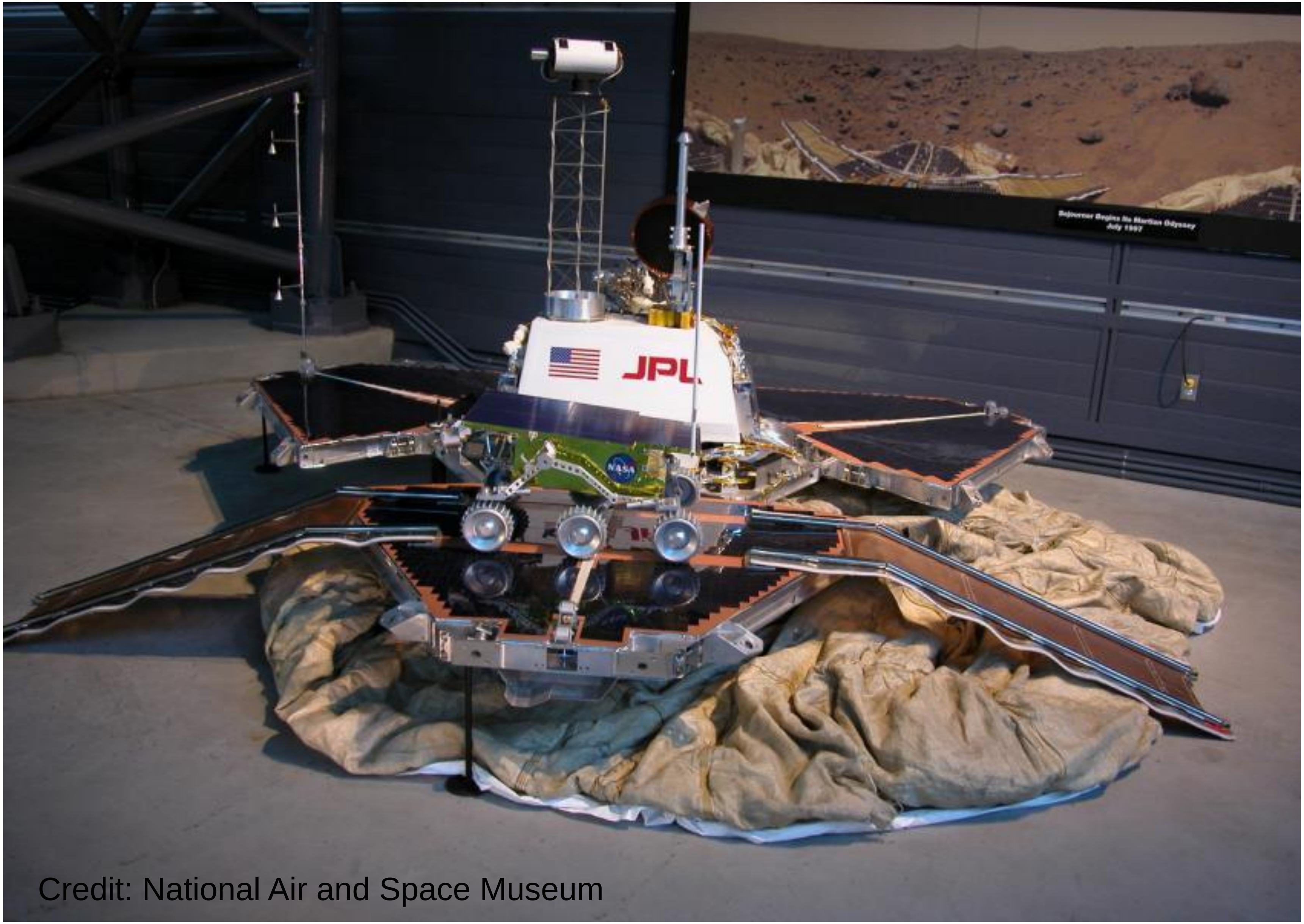
Understand the geological processes affecting Mars' interior, crust, and surface

Develop Knowledge & Technology Necessary for Eventual Human Exploration

When • Where • Form • Amount

Credit: NASA/Orlando Figueroa

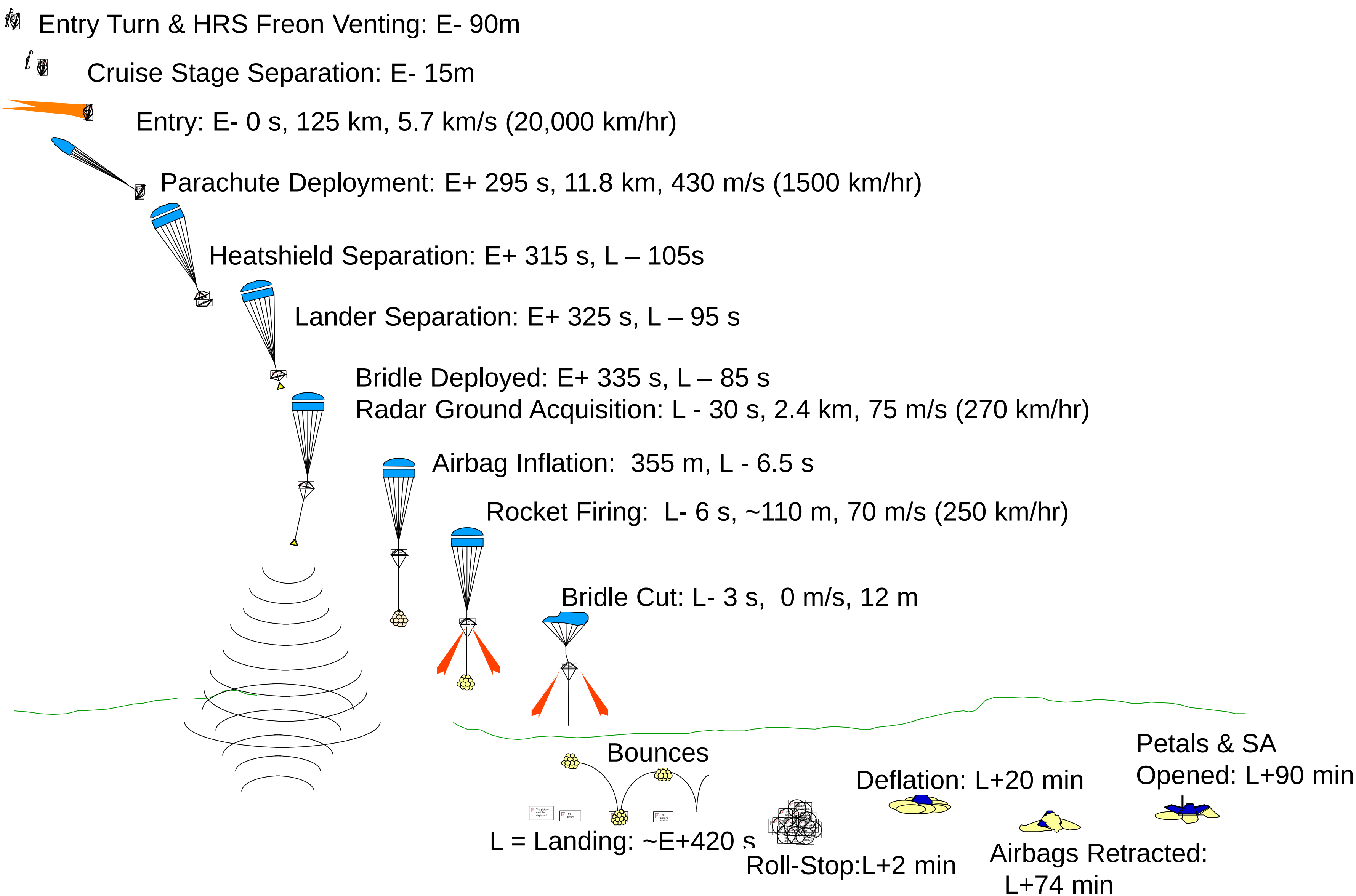
# Mars Pathfinder (1997)



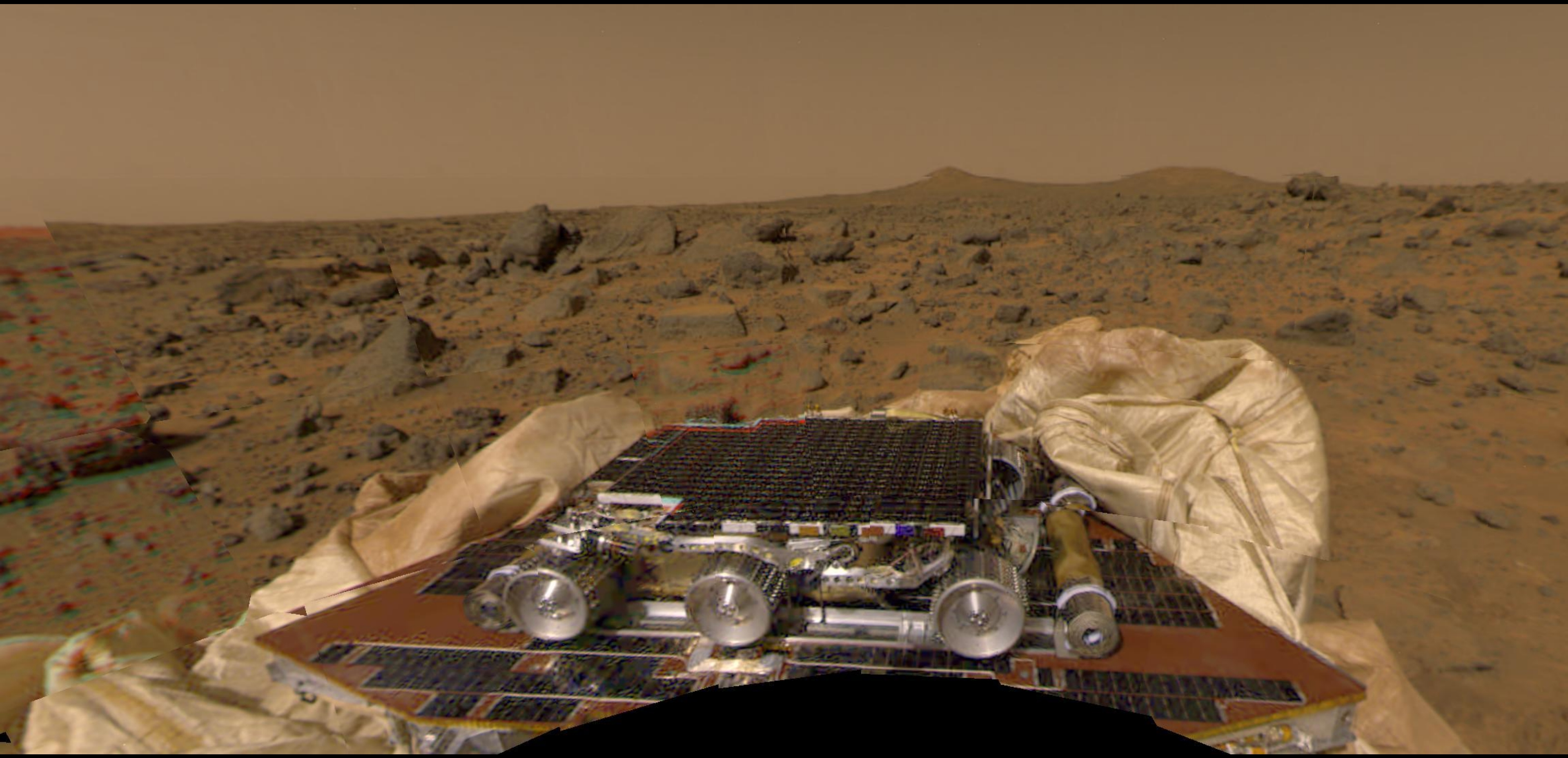
Credit: National Air and Space Museum

# Mars Pathfinder (1997)

# Entry, Descent & Landing Timeline



# July 4, 1997

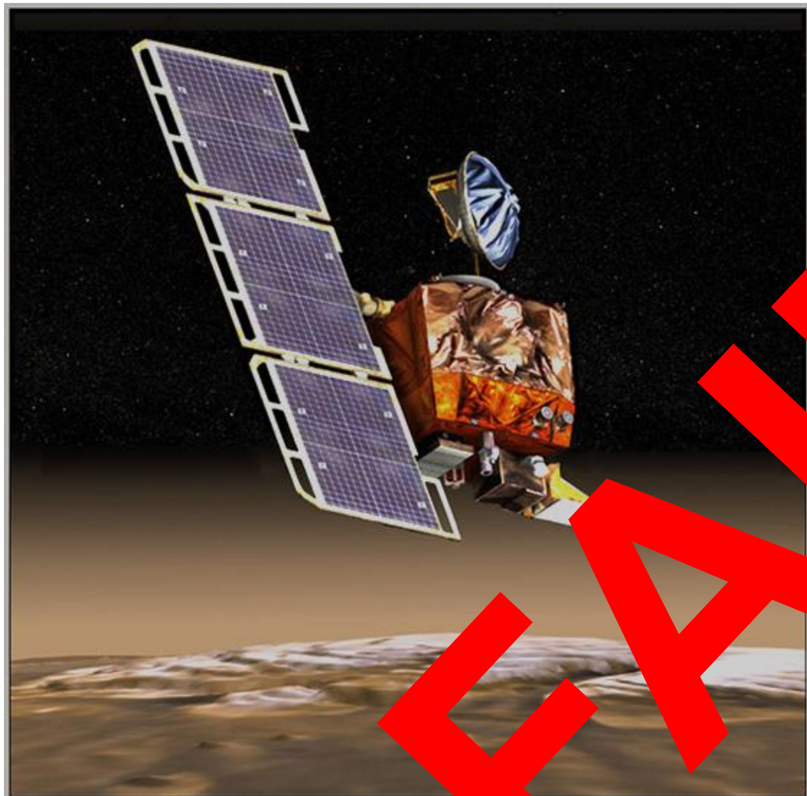


# Sojourner Rover and Yogi

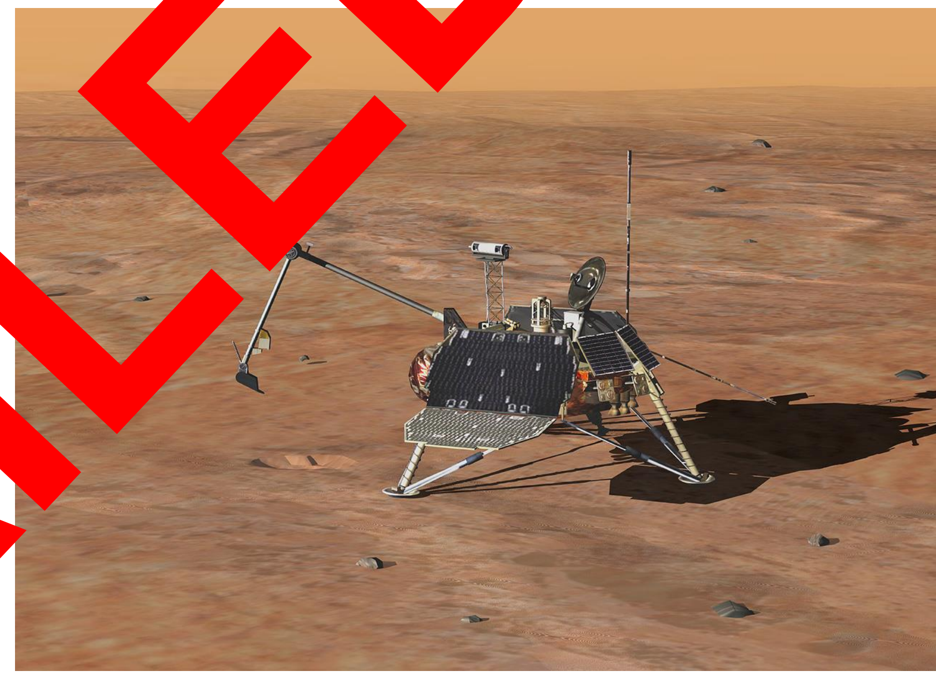
## Mars Climate Orbiter

## Mars Polar Lander

**FAILED**

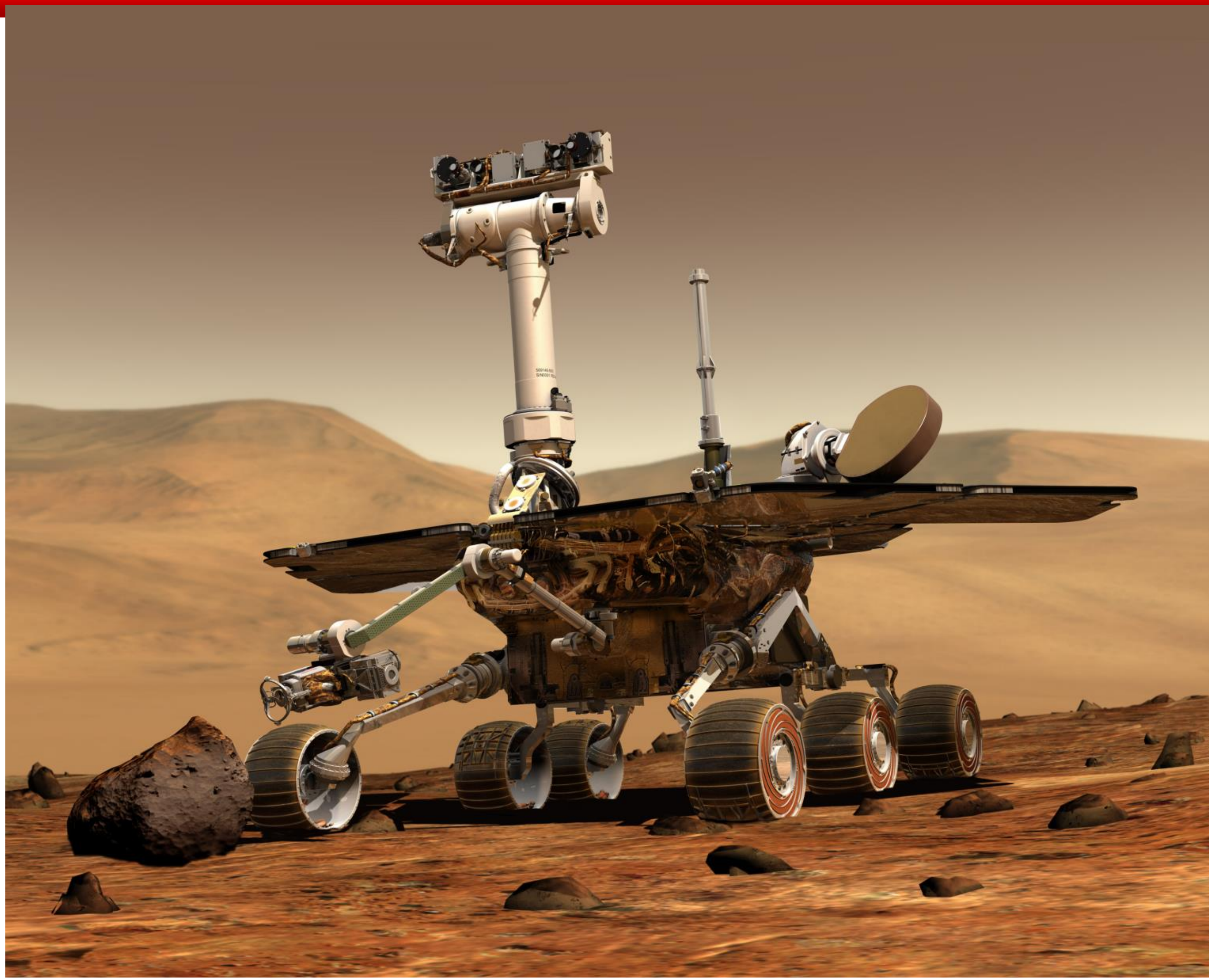


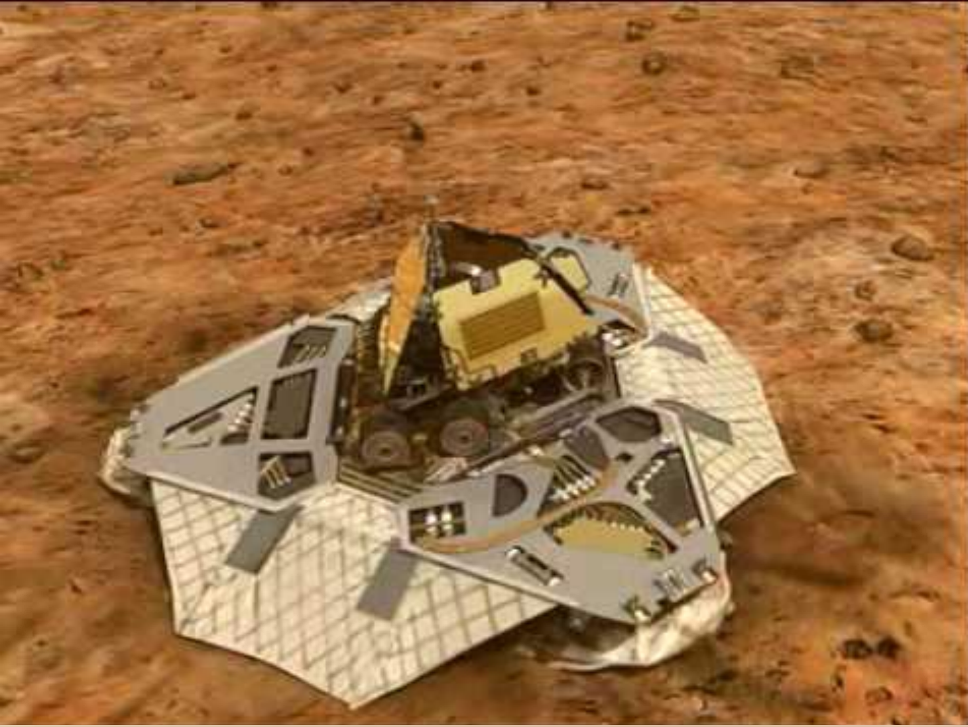
September 23, 1999

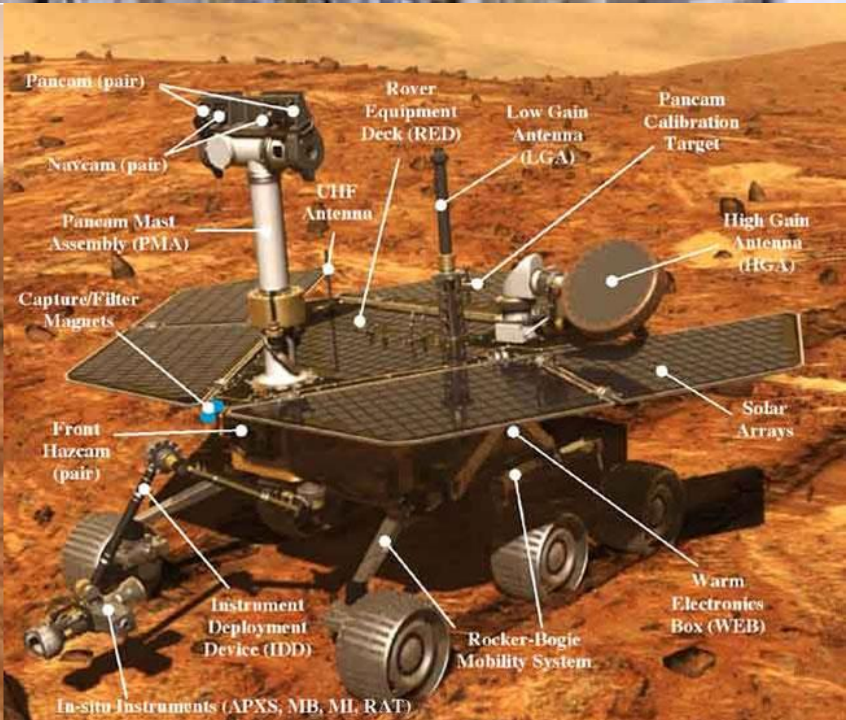


December 23, 1999

# Spirit/Opportunity Rovers (2004)



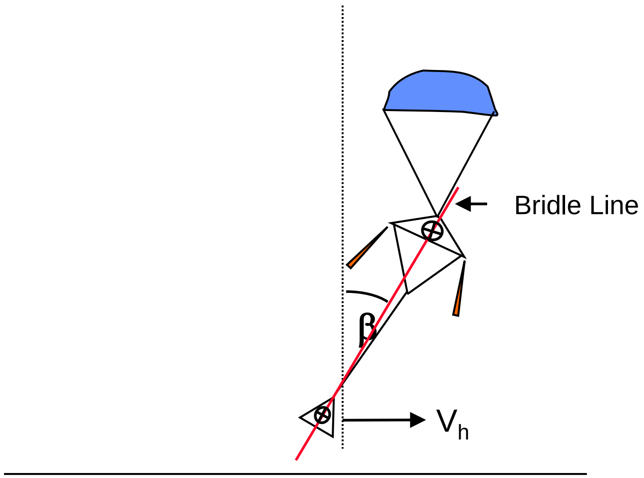



Pancam (pair)
Navcam (pair)
Rover Equipment Deck (RED)
Low Gain Antenna (LGA)
Pancam Calibration Target
UHF Antenna
Pancam Mast Assembly (PMA)
High Gain Antenna (HGA)
Capture/Filter Magnets
Solar Arrays
Front Hazcam (pair)
Warm Electronics Box (WEB)
Instrument Deployment Device (IDD)
Rocker-Bogie Mobility System
In-situ Instruments (APXS, MB, MI, RAT)

# Sources of Horizontal Velocity



- **Definitions:**
  - *Initial Horizontal Velocity*
    - Steady State winds
    - Parachute instability (I.e. trim angle) induced
  - *RAD Induced Horizontal Velocity*
    - Wind Shear
    - Parachute instability
    - Uncontrolled
      - RAD rockets thrust mismatch induced
      - RAD rockets misalignment induced
      - Backshell c.o.m. offset induced
      - Bridal confluence point offset induced



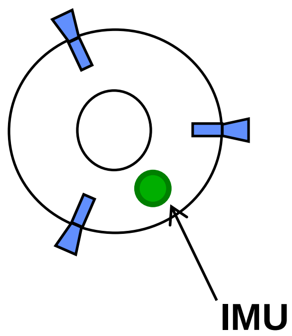

$$V_h(t_{bc}) = \underbrace{V_h(t_{RAD})}_{\text{Initial Horizontal Velocity}} + \underbrace{\int F_{RAD}/m * \sin(\beta)\, dt}_{\text{RAD Induced Horizontal Velocity}}$$

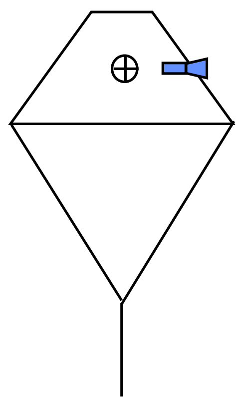
- **Example:**
  - a 20 degrees Bridle Angle angle results in an horizontal velocity of 29 m/s

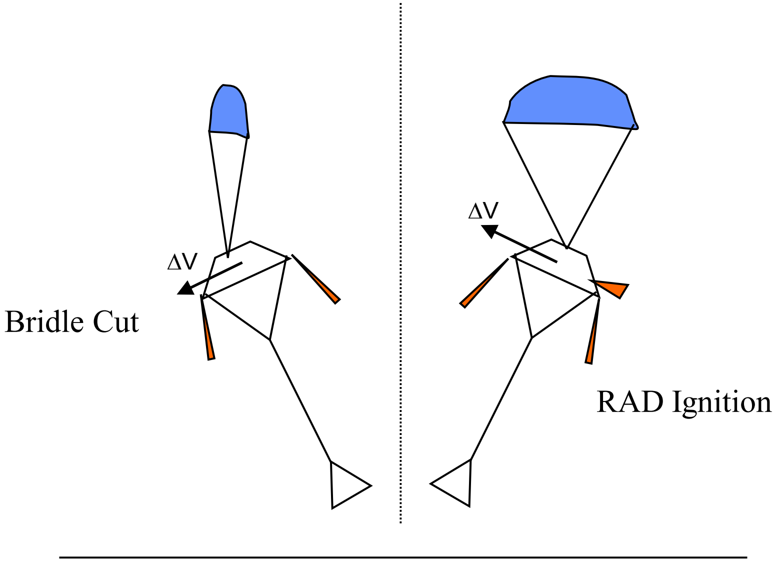
# TIRS Control



- **Add three small rockets aimed at the backshell c.o.m. to impart impulsively a transverse delta-V to the backshell in order to reduce the average off-nadir angle during RAD firing.**
  - Transverse Impulse Rocket System (TIRS)
  - Backshell deltaV = 5 m/sec
    - 40 degrees bridle angle correction in 3.3 sec of RAD firing
  - TIRS burn duration < 0.5 seconds



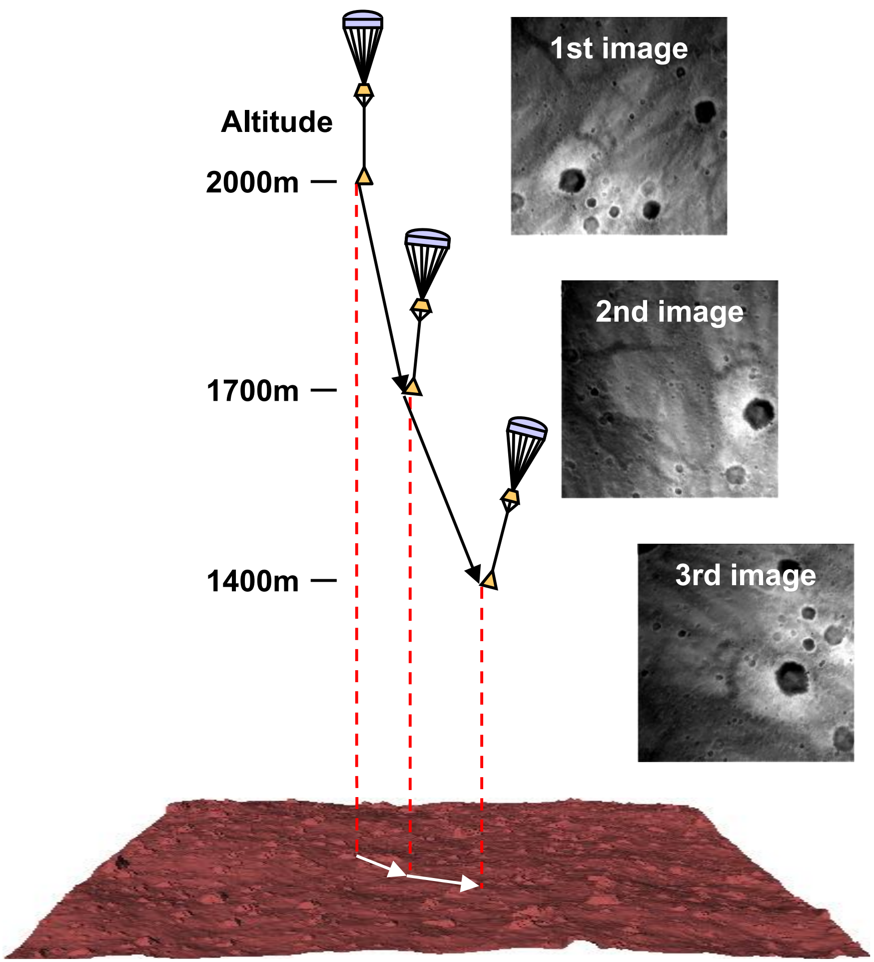



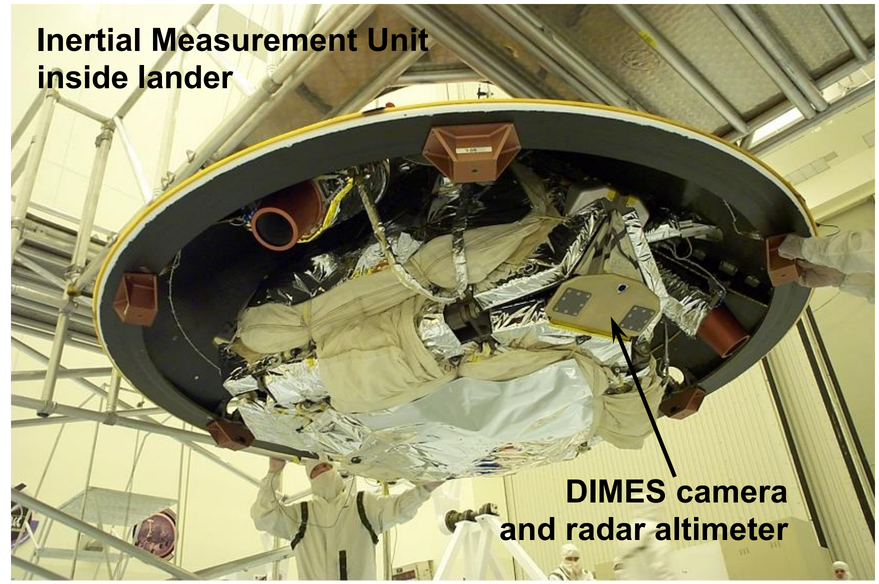


# Descent Image Motion Estimation System (DIMES)

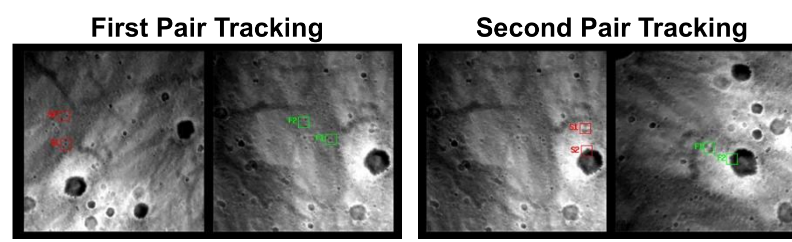
Mars Exploration Rover

## DIMES SCENARIO



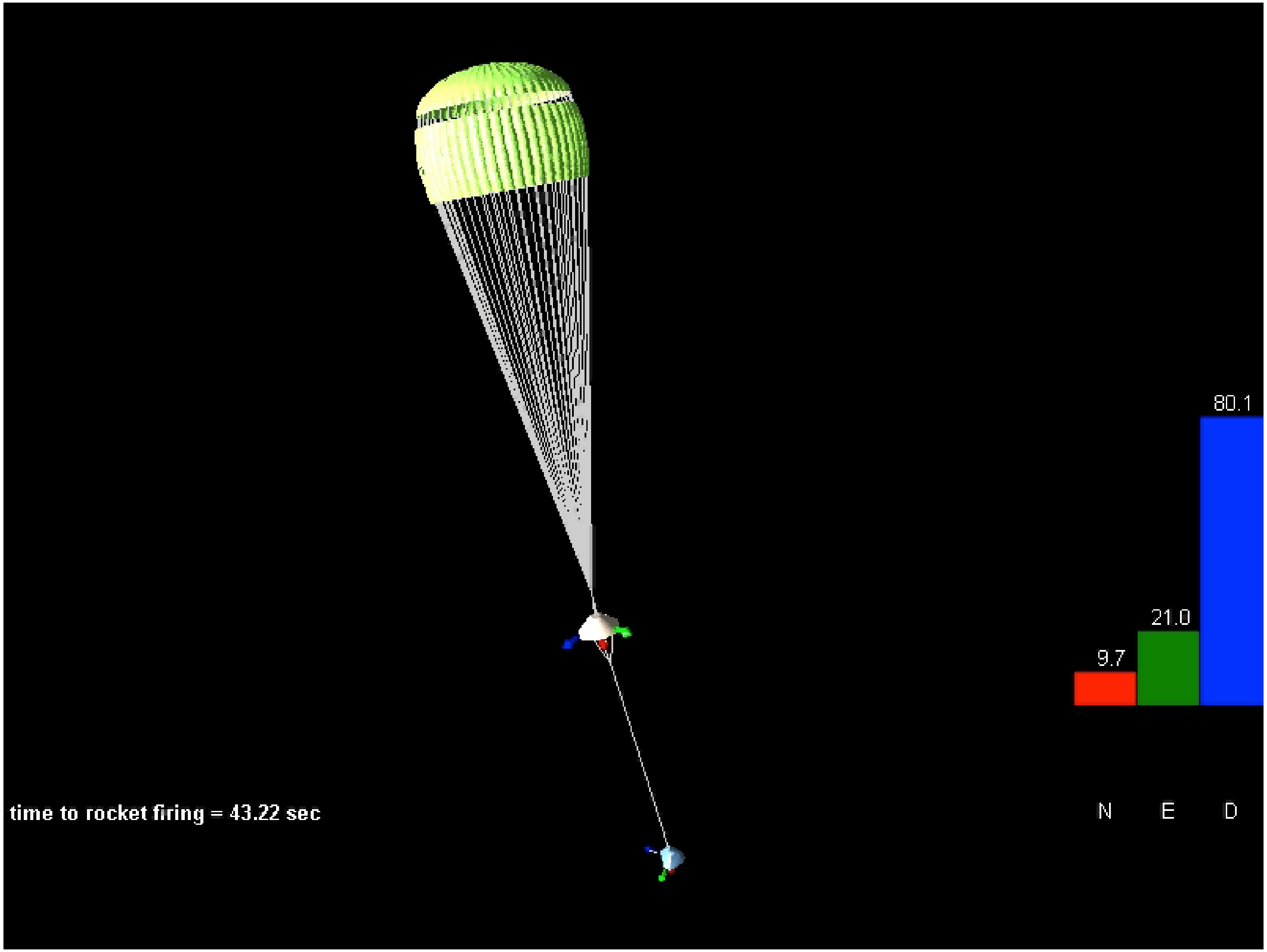

## DIMES RESULT



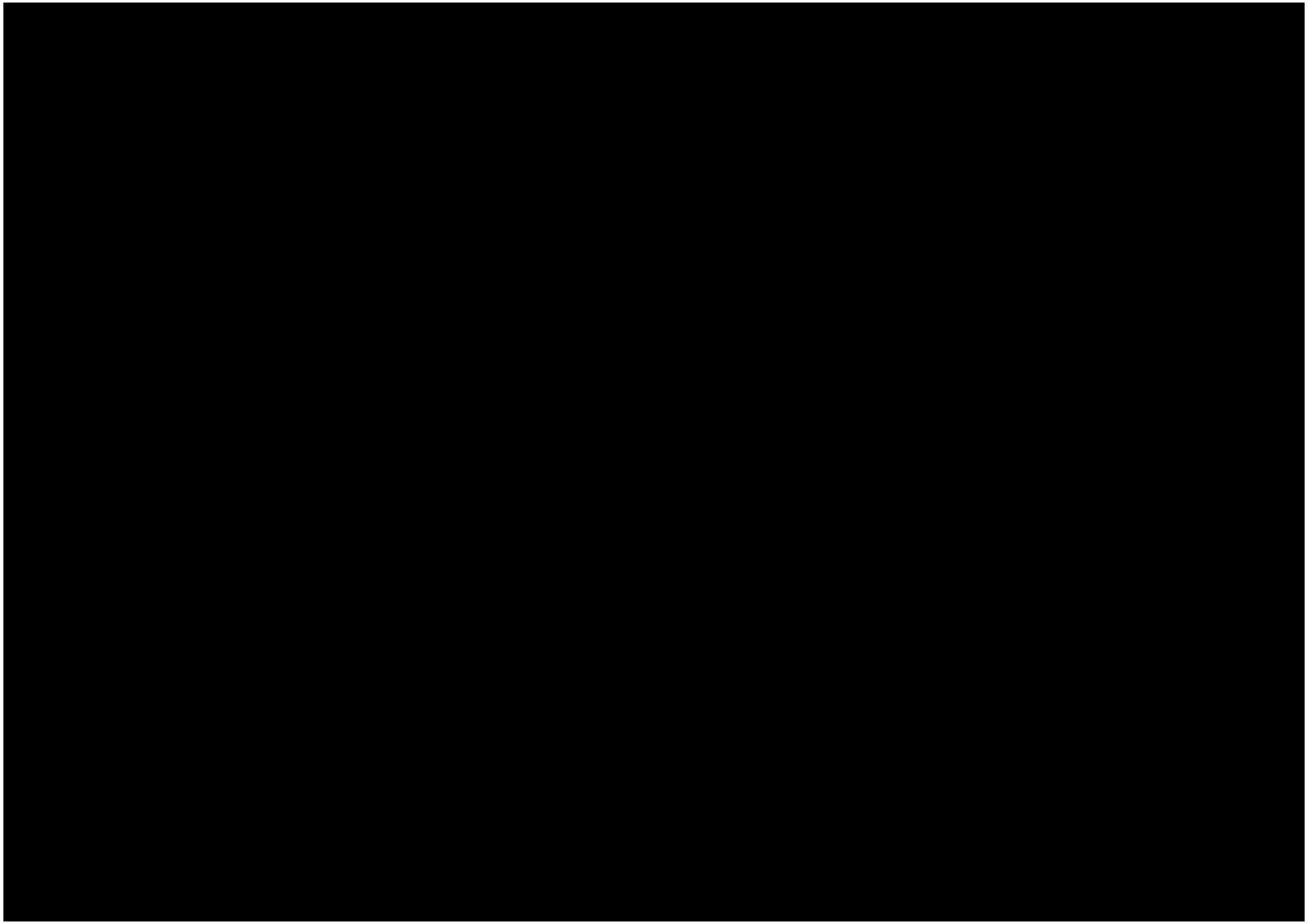

MER-A/Spirit, Gusev Crater, January 4th, 2004

# Spirit Reconstruction Movie

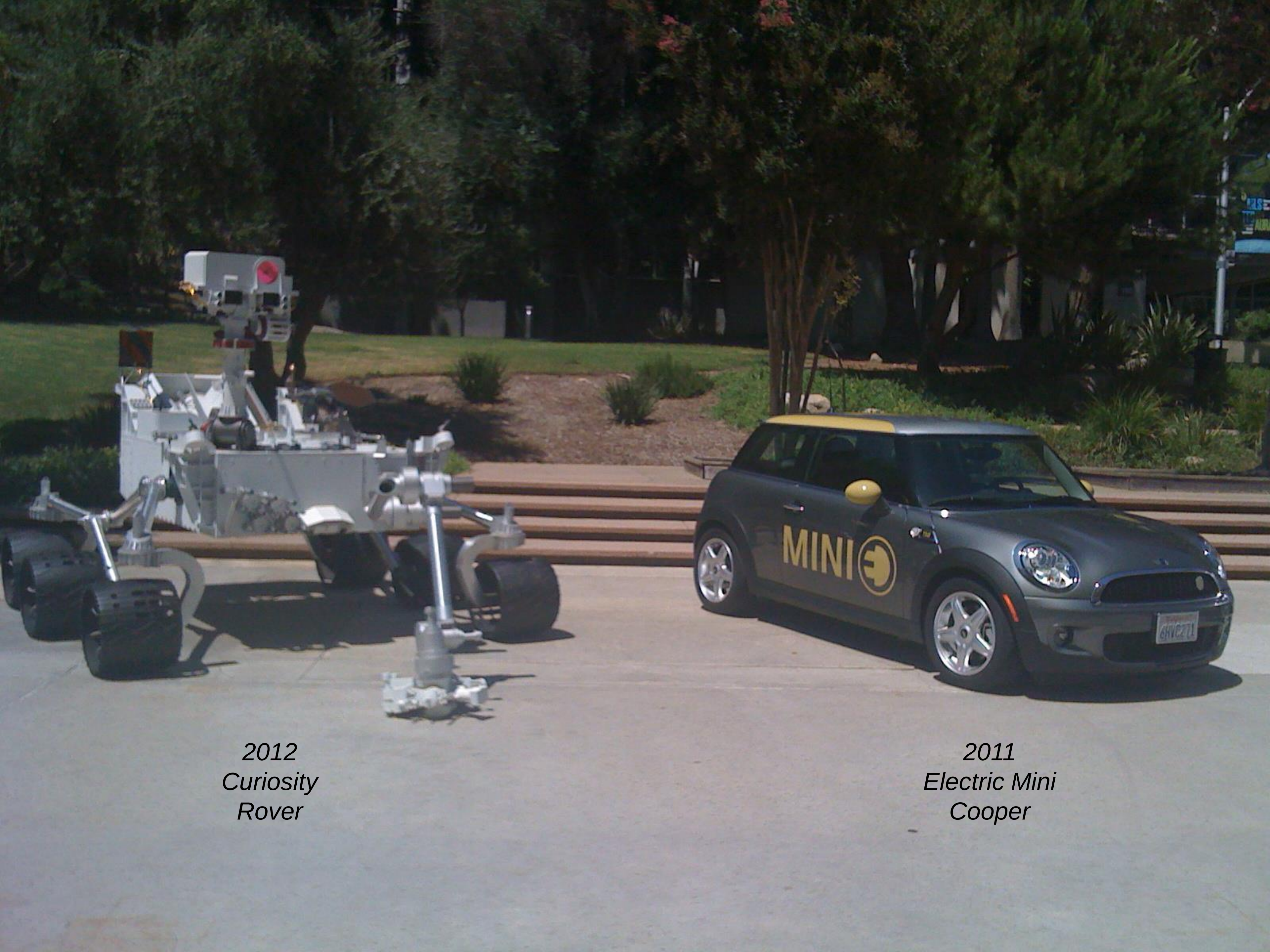
*Mars Exploration Rover*



# Spirit Landing in January 2004

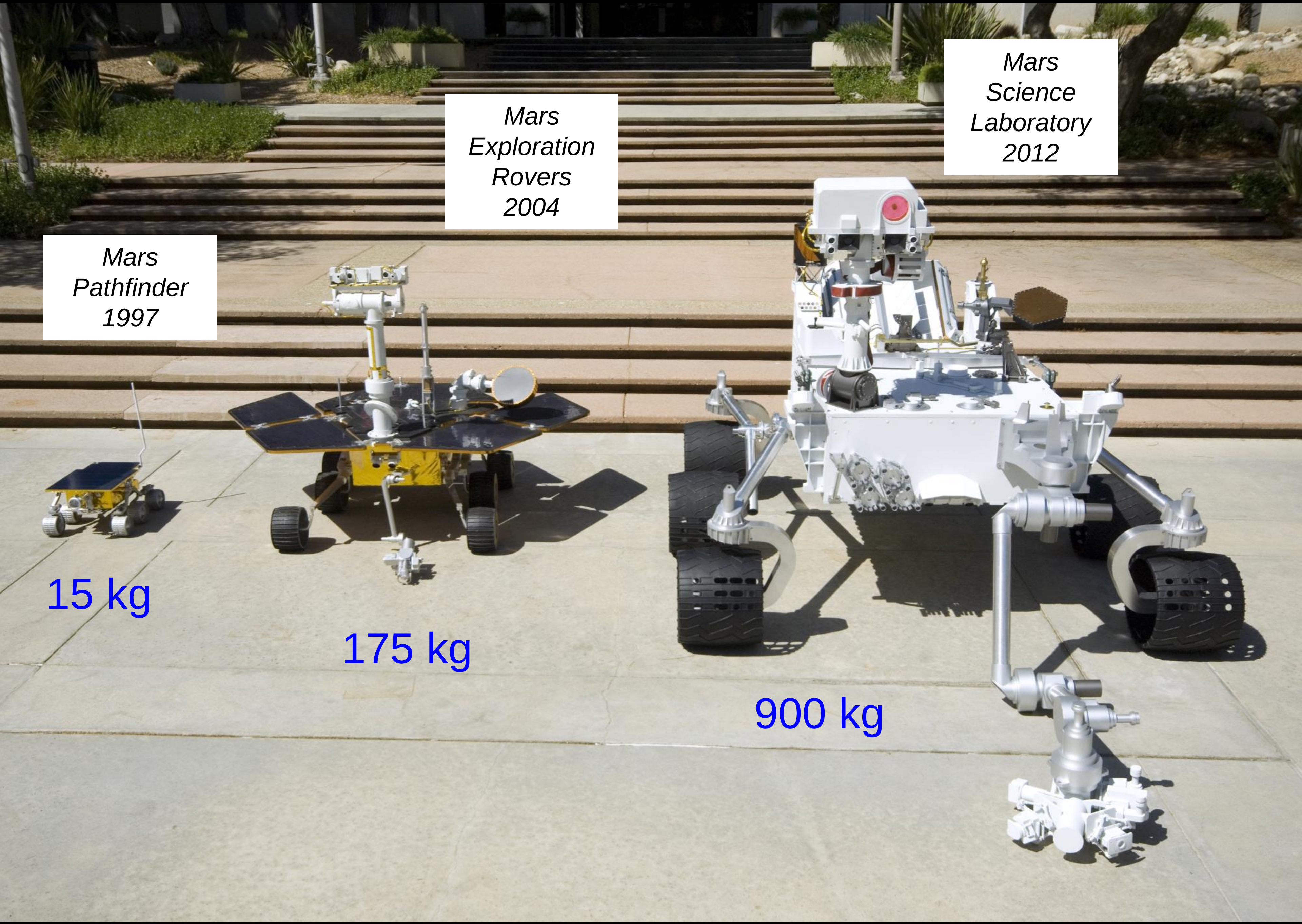


# Rover Egress

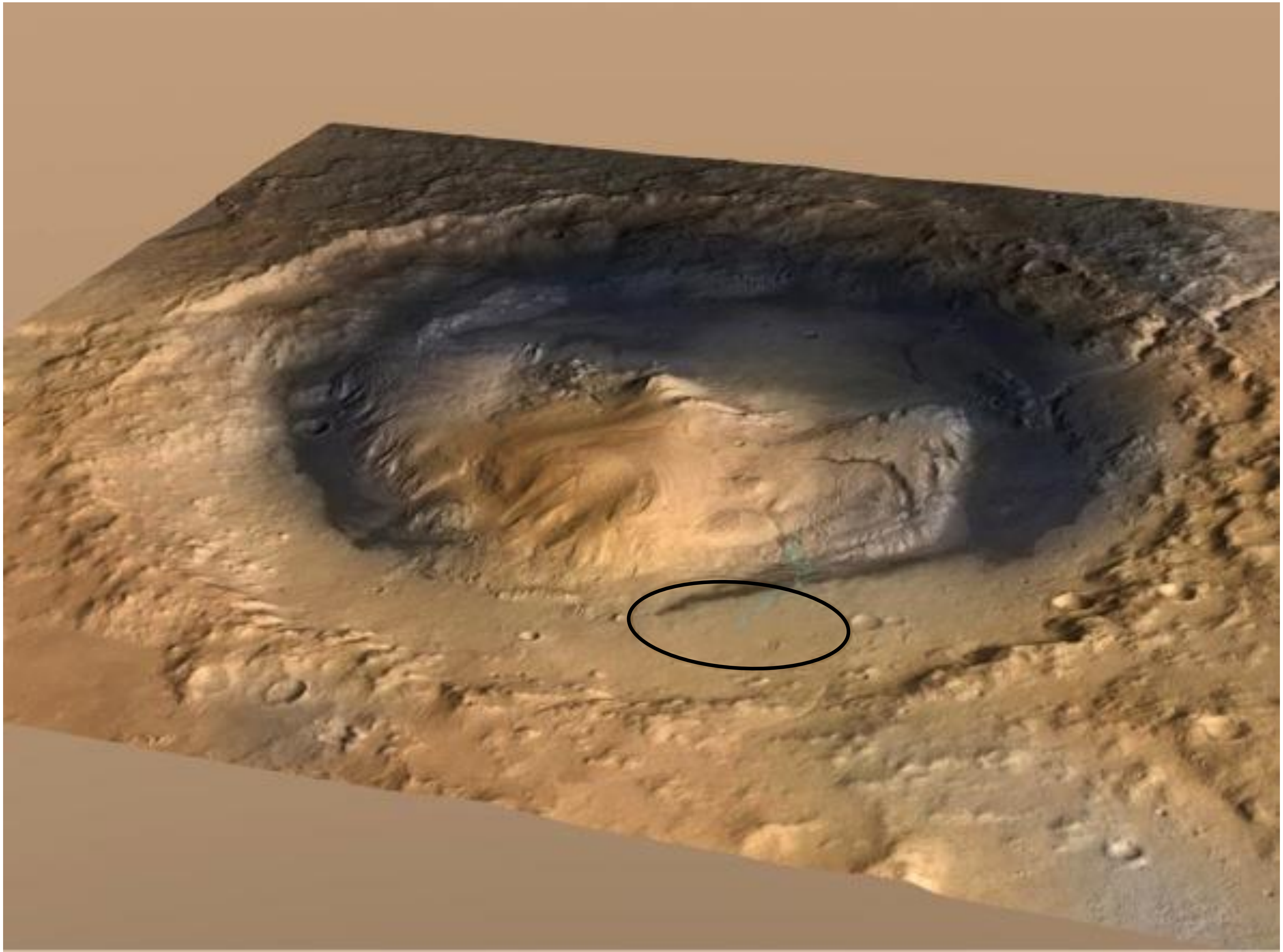


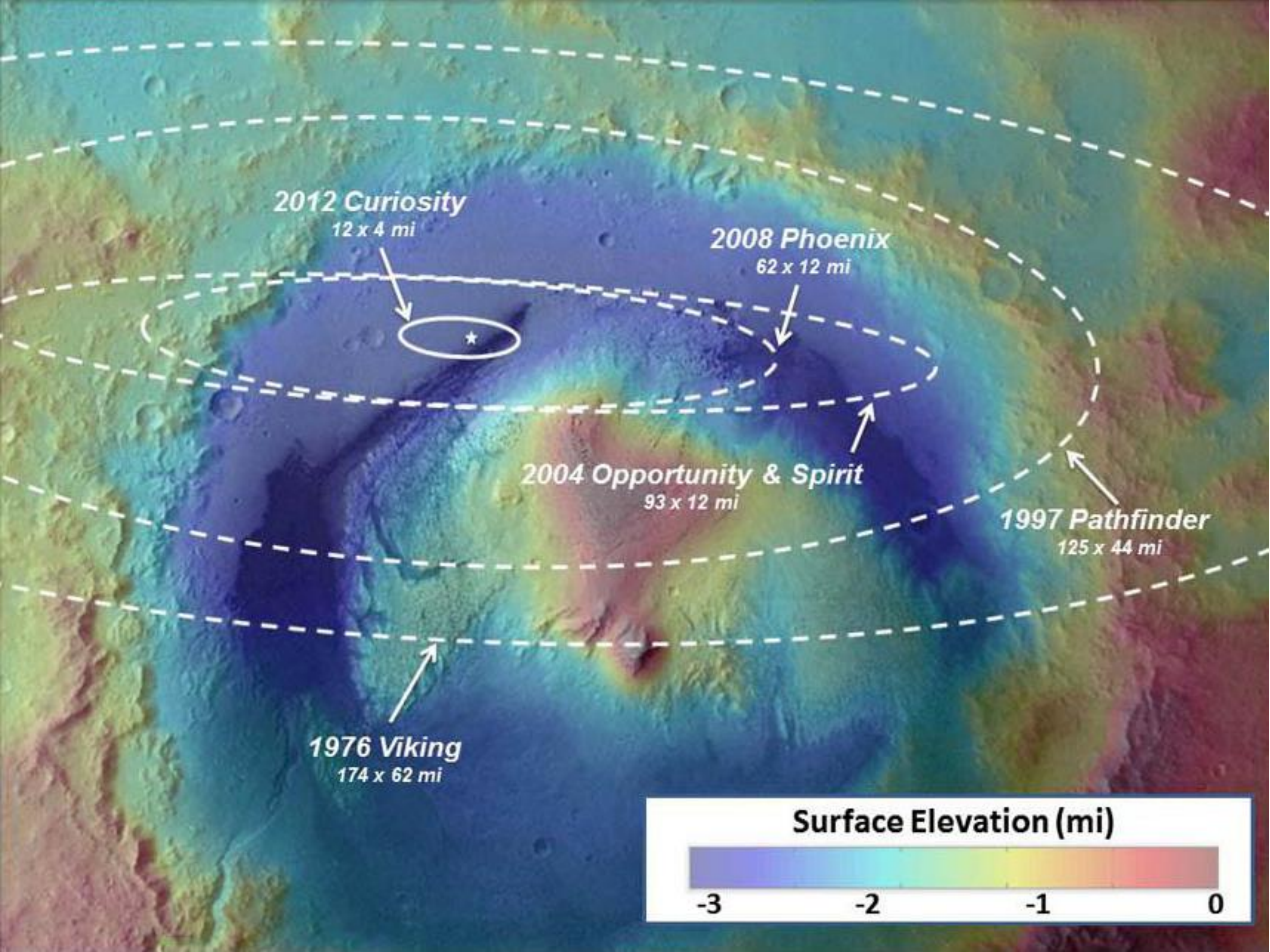

*2012*
*Curiosity*
*Rover*

*2011*
*Electric Mini*
*Cooper*


Mars Pathfinder 1997
Mars Exploration Rovers 2004
Mars Science Laboratory 2012
15 kg
175 kg
900 kg

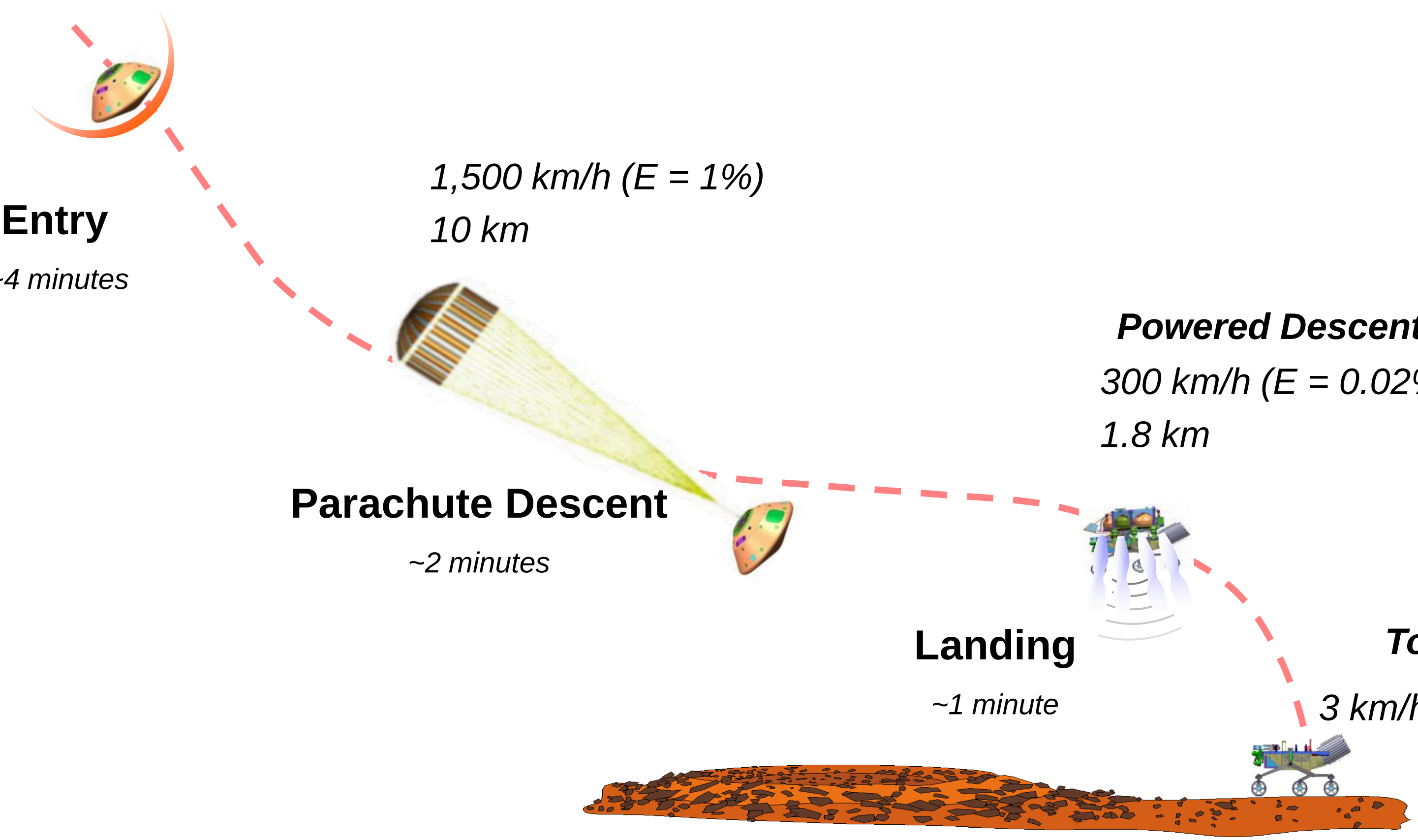
# MSL/Curiosity Landing Ellipse in Gale Crater



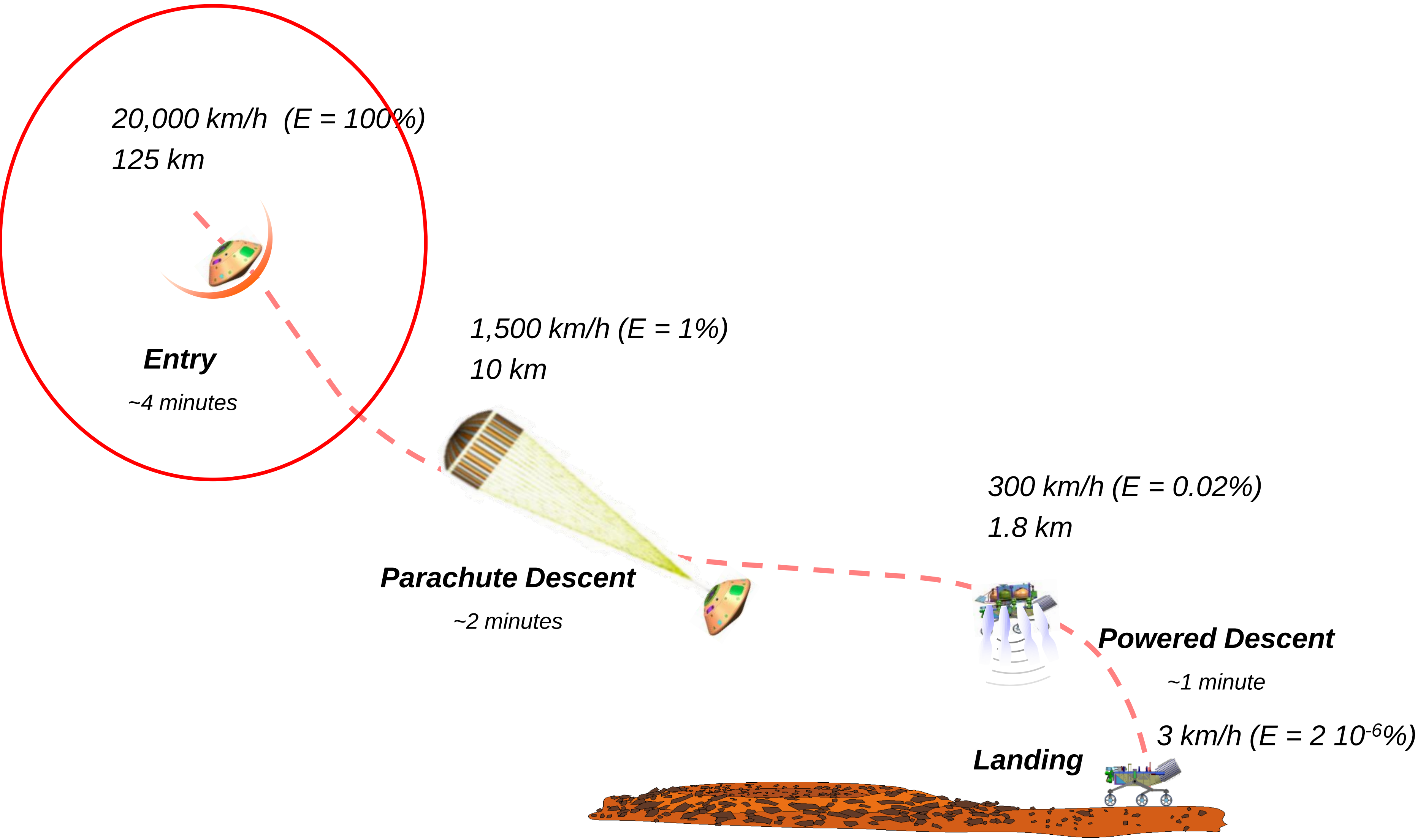

2012 Curiosity
12 x 4 mi
2008 Phoenix
62 x 12 mi
2004 Opportunity & Spirit
93 x 12 mi
1997 Pathfinder
125 x 44 mi
1976 Viking
174 x 62 mi
Surface Elevation (mi)
-3
-2
-1
0

# Entry, Descent, and Landing Phases

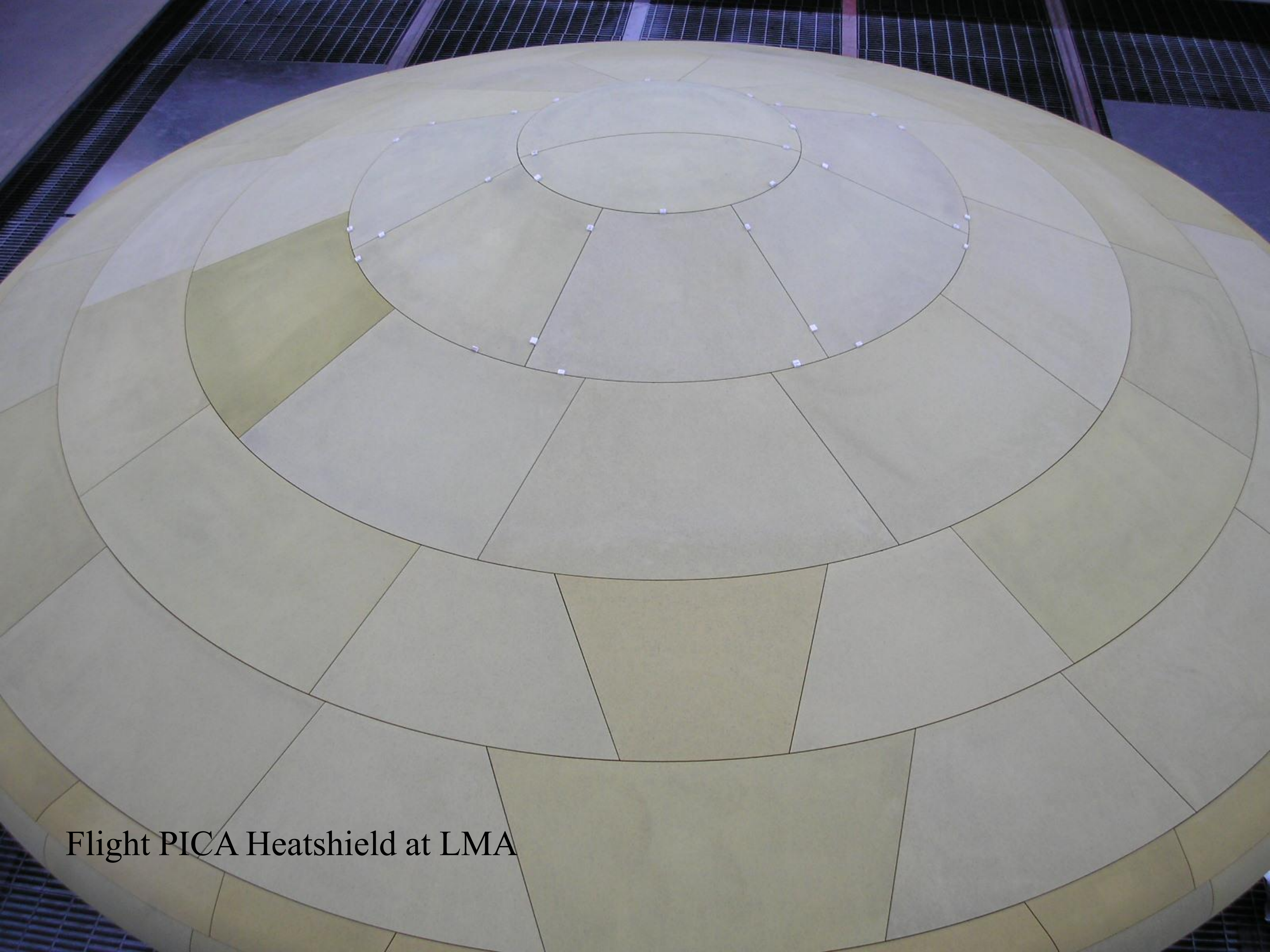
## *The 7 Minutes of Terror*



# Entry, Descent, and Landing Phases

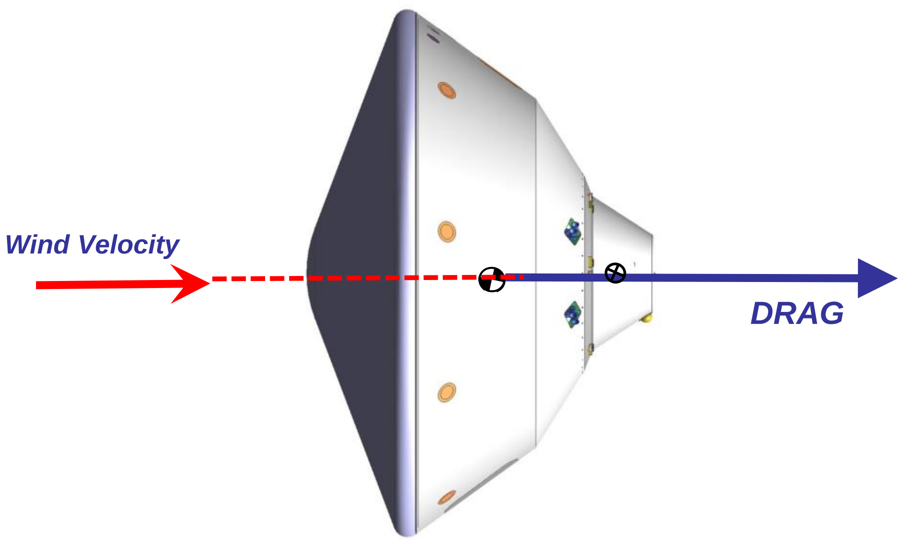


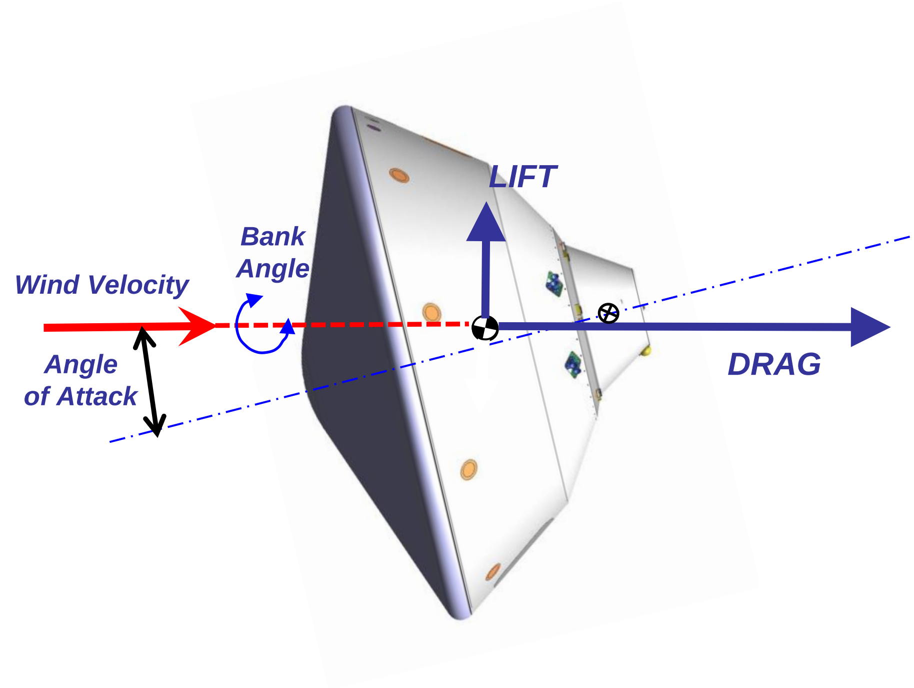
# MSL Aeroshell



Flight PICA Heatshield at LMA

# Ballistic vs. Lifting Entry

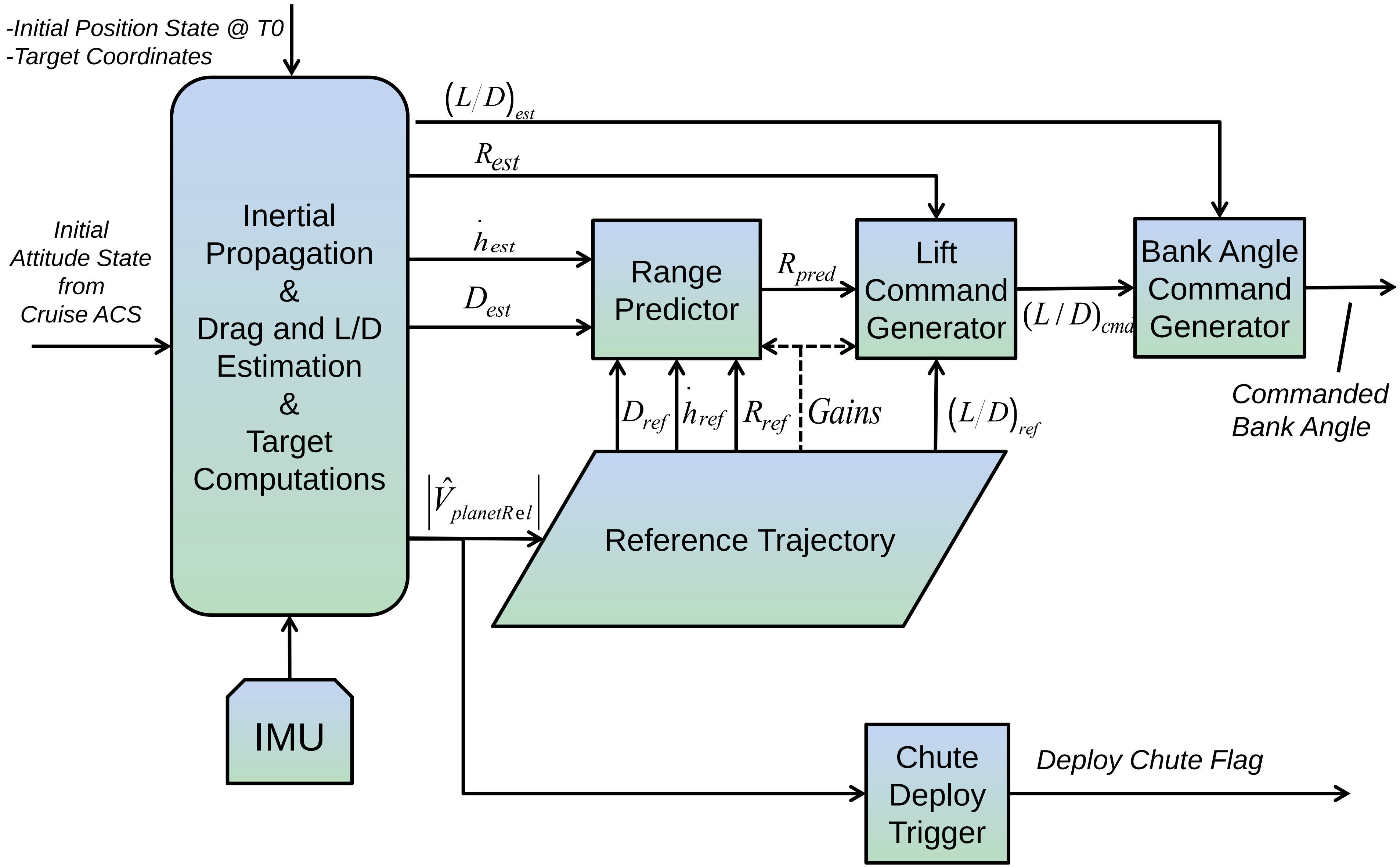


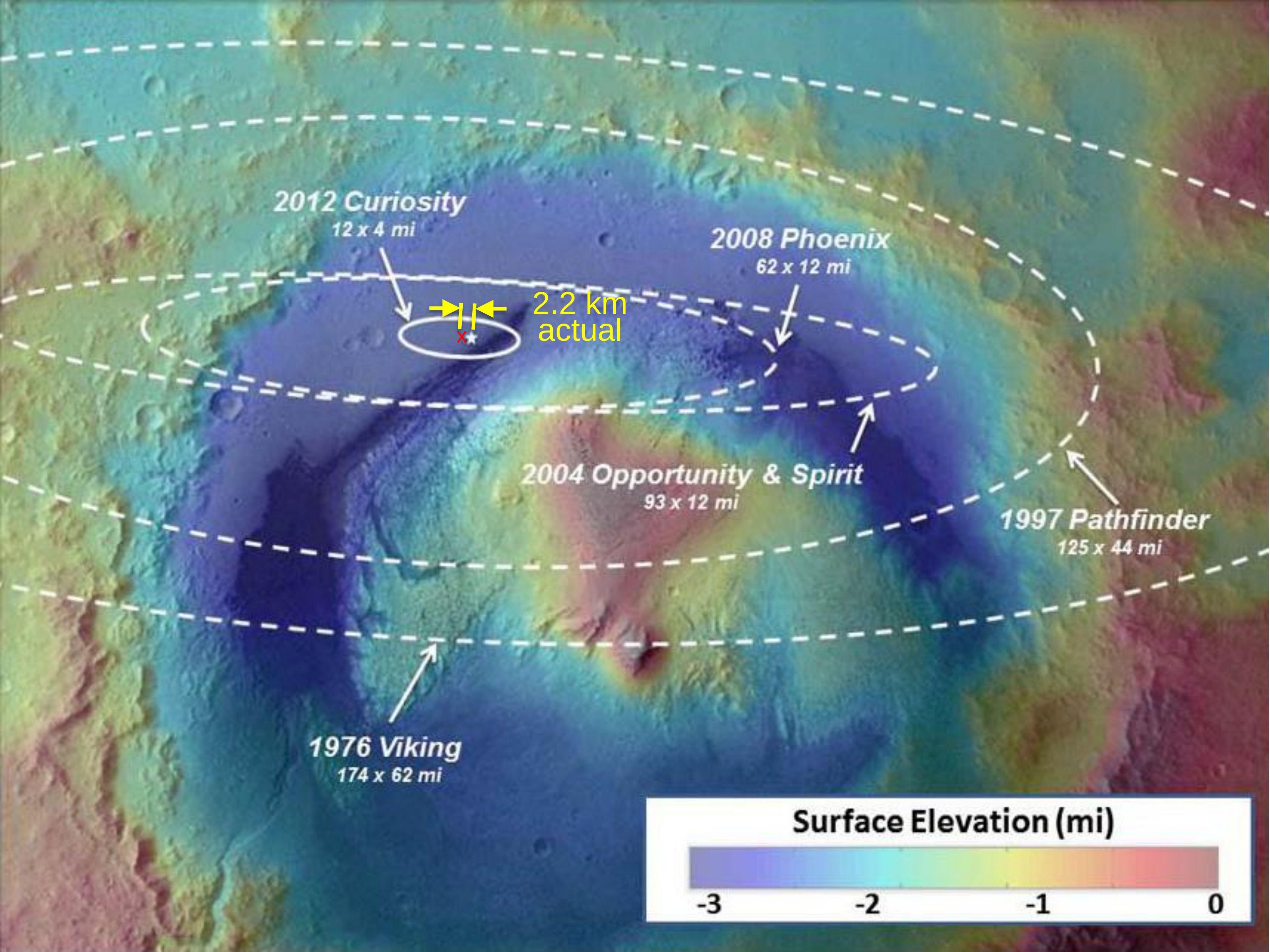




**Ballistic Entry**
(Pathfinder/MER/Phoenix)

**Lifting Entry**
(Viking, Curiosity)

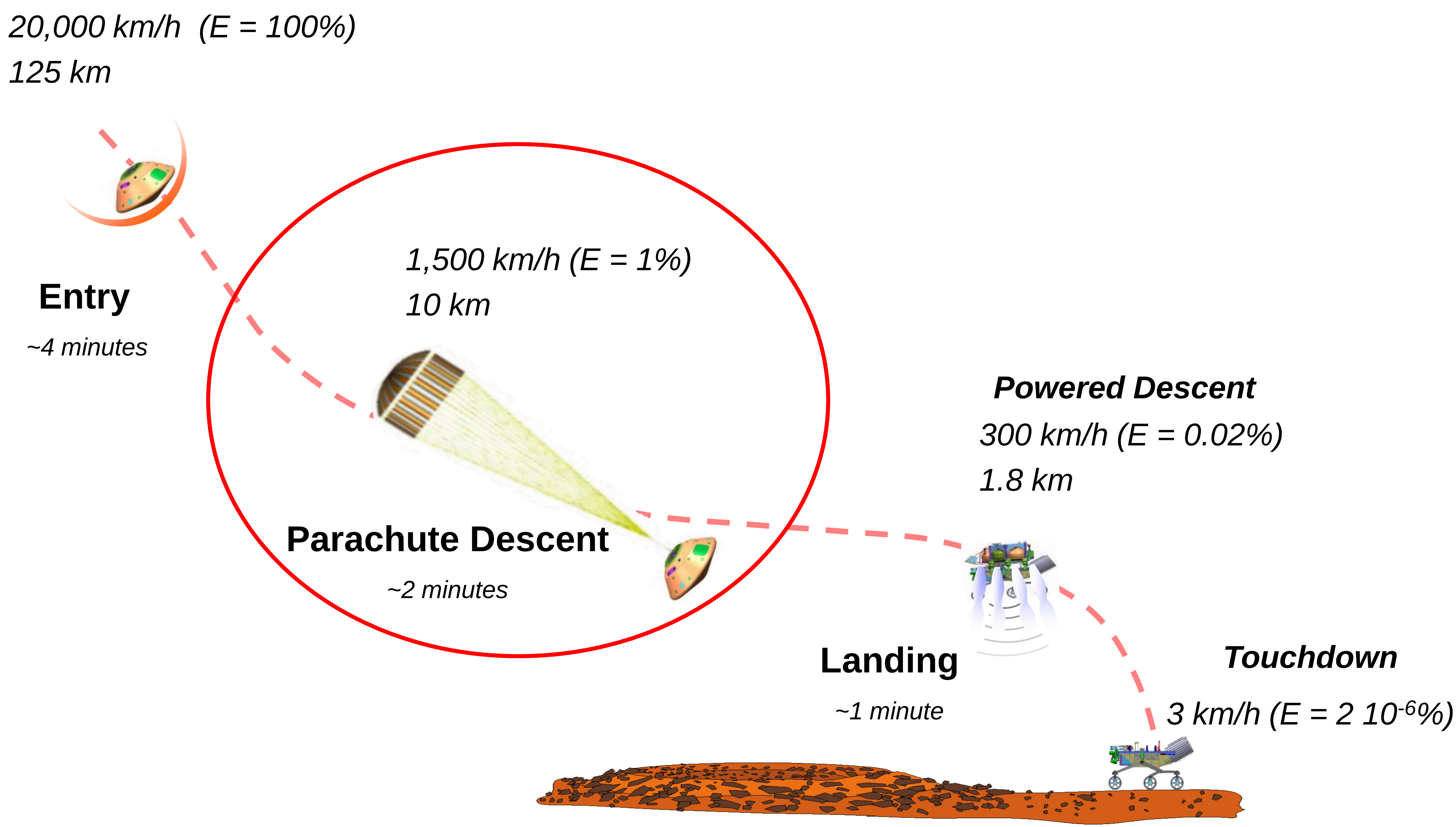
# Apollo Based Range Entry Guidance





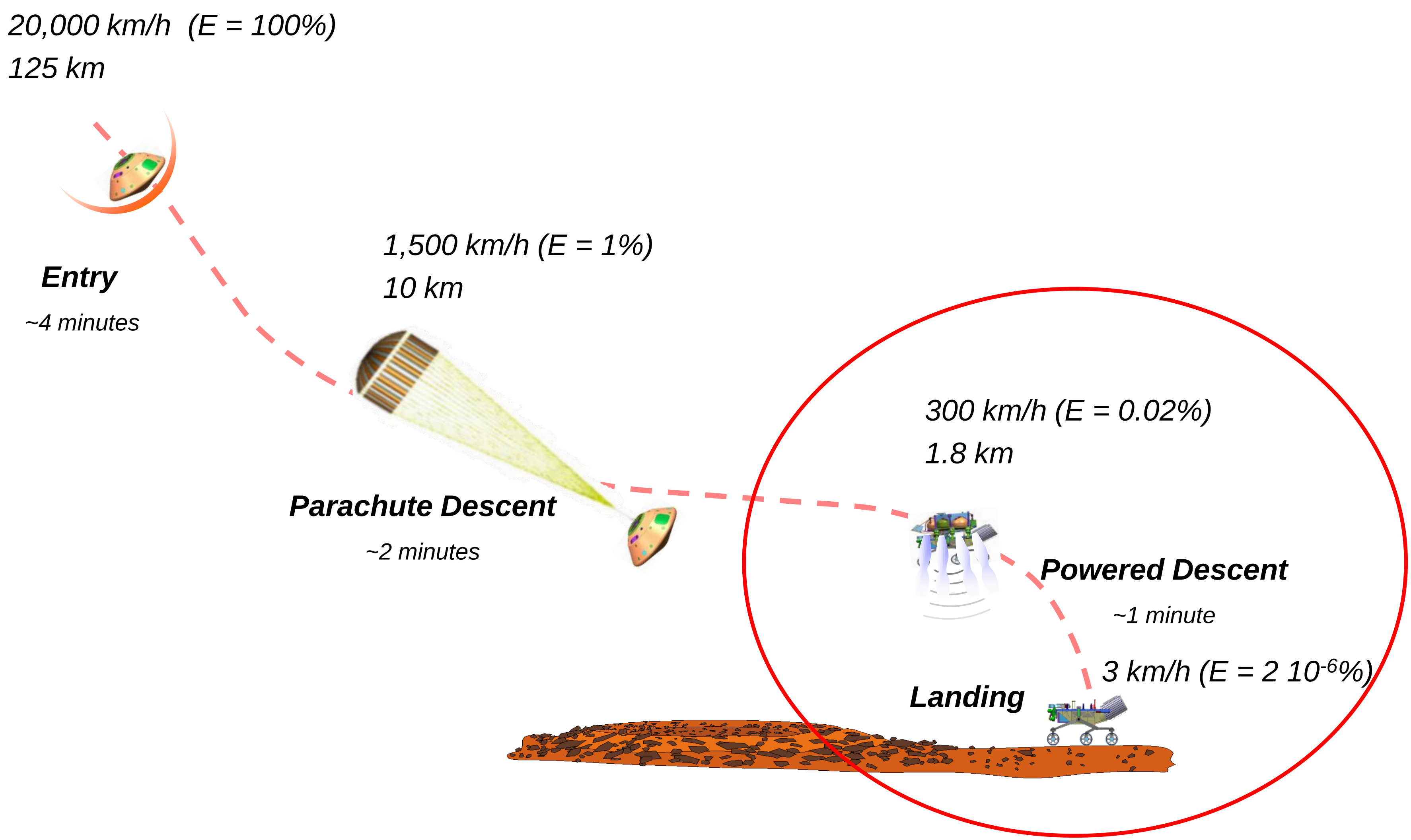
2012 Curiosity
12 x 4 mi
2.2 km
actual
2008 Phoenix
62 x 12 mi
2004 Opportunity & Spirit
93 x 12 mi
1997 Pathfinder
125 x 44 mi
1976 Viking
174 x 62 mi
Surface Elevation (mi)
-3
-2
-1
0

# Entry, Descent, and Landing Phases

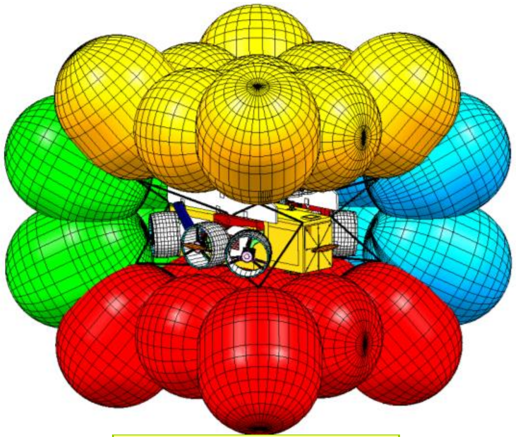


# Worlds Largest Supersonic Parachute

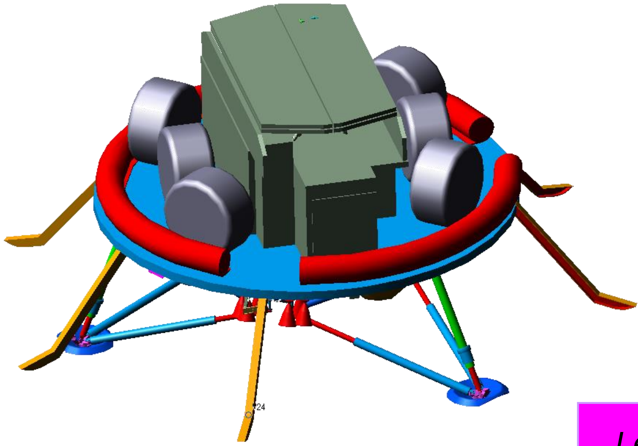
# Entry, Descent, and Landing Phases

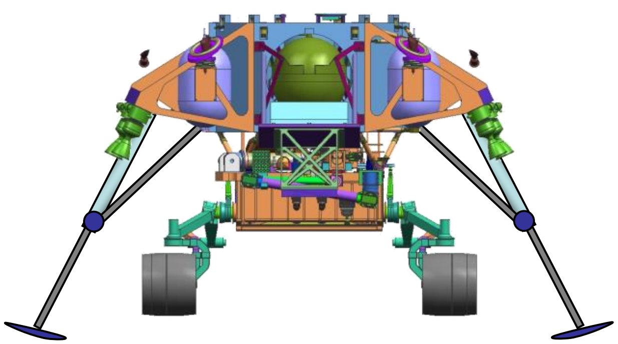


# How to land a 1 ton rover?

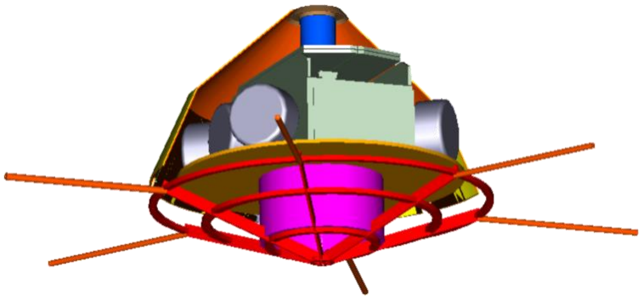


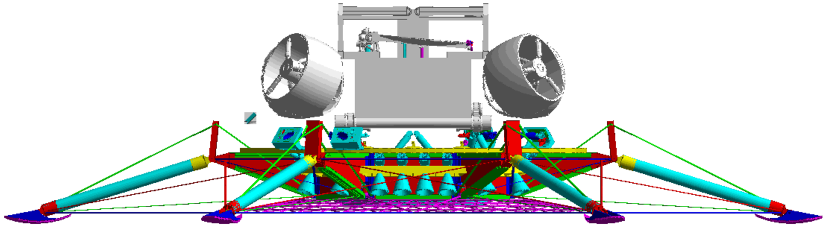
*Airbags*





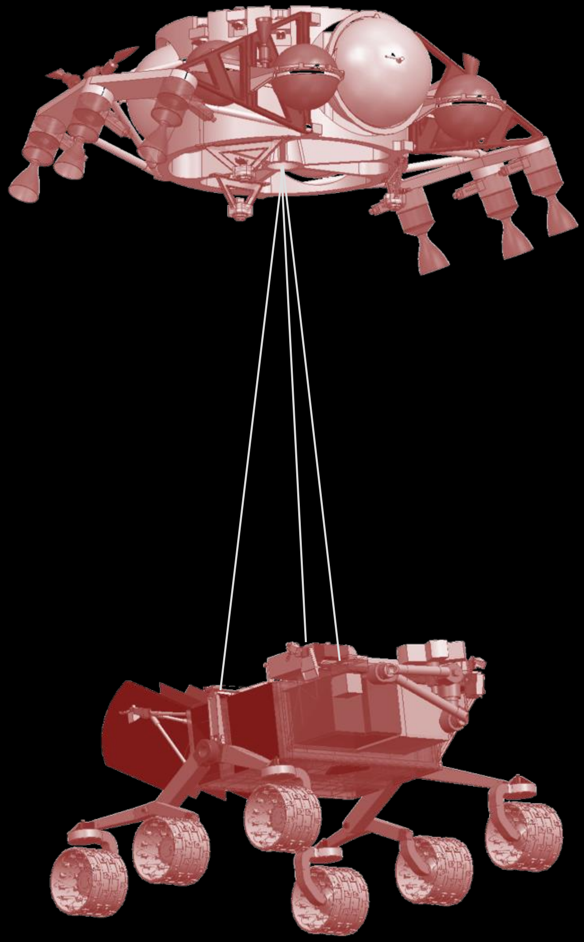
*Legs*

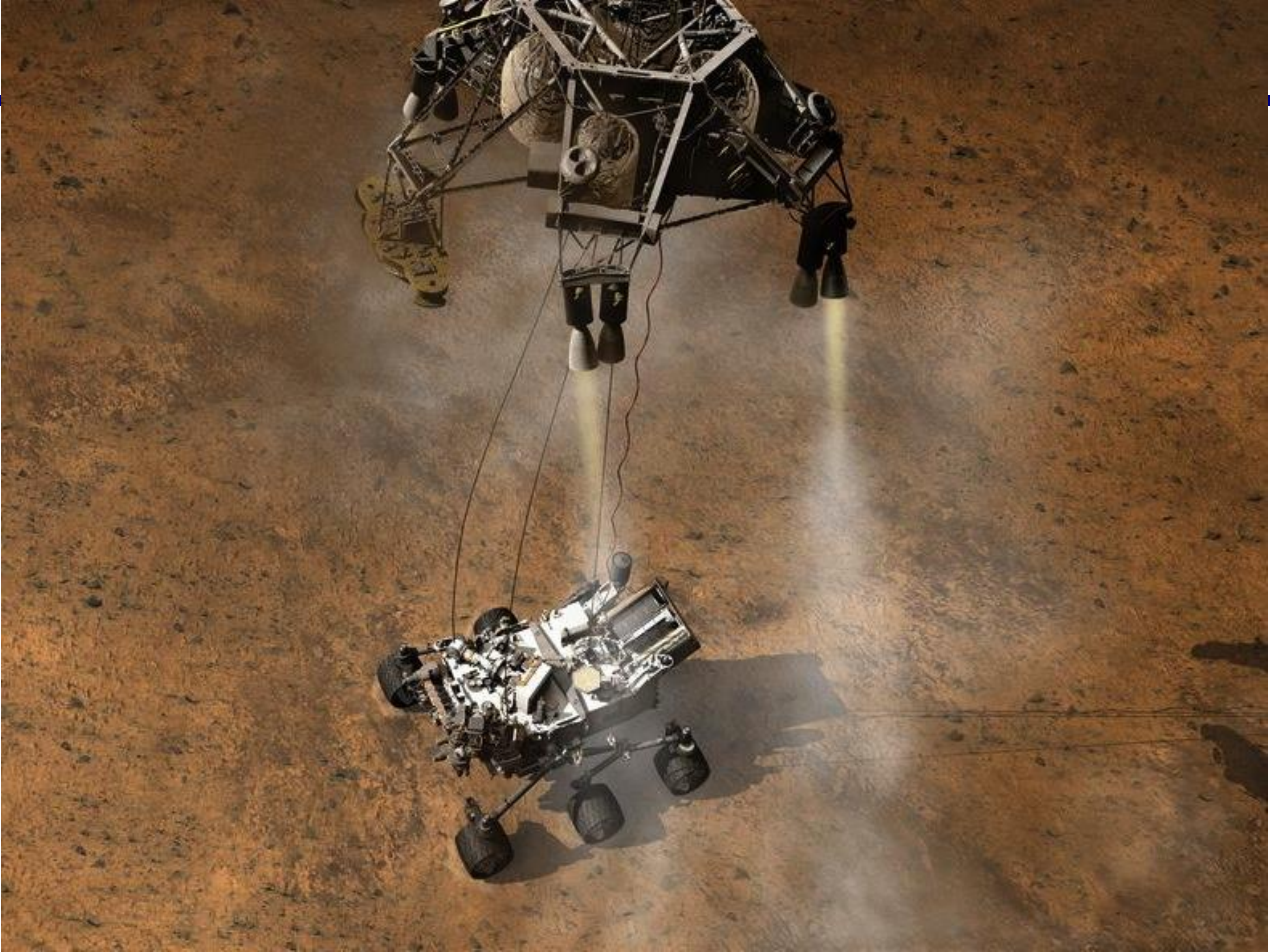




*Pallet*

# 2003: The Skycrane maneuver is born

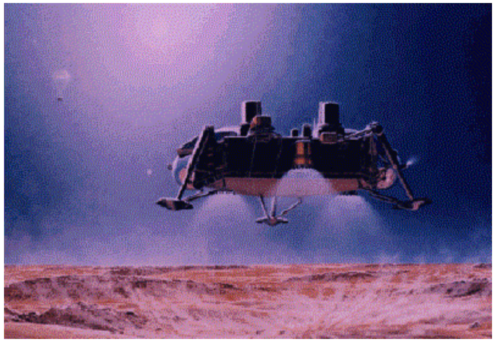




# Motivation Behind The SkyCrane

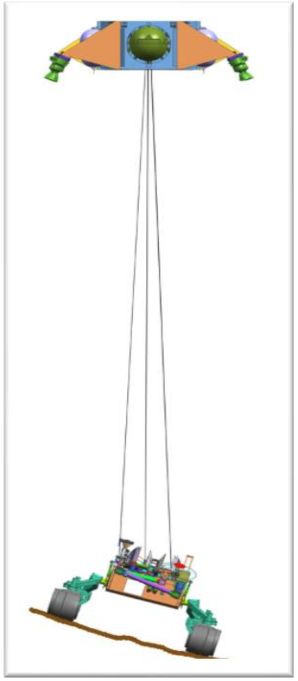
Touchdown Velocity:
- Vv = 12m/sec
- Vh < 16m/sec

+



Towchdown Velocity:
- Vv = 2.4 m/sec
- Vh < 1.4 m/sec

=



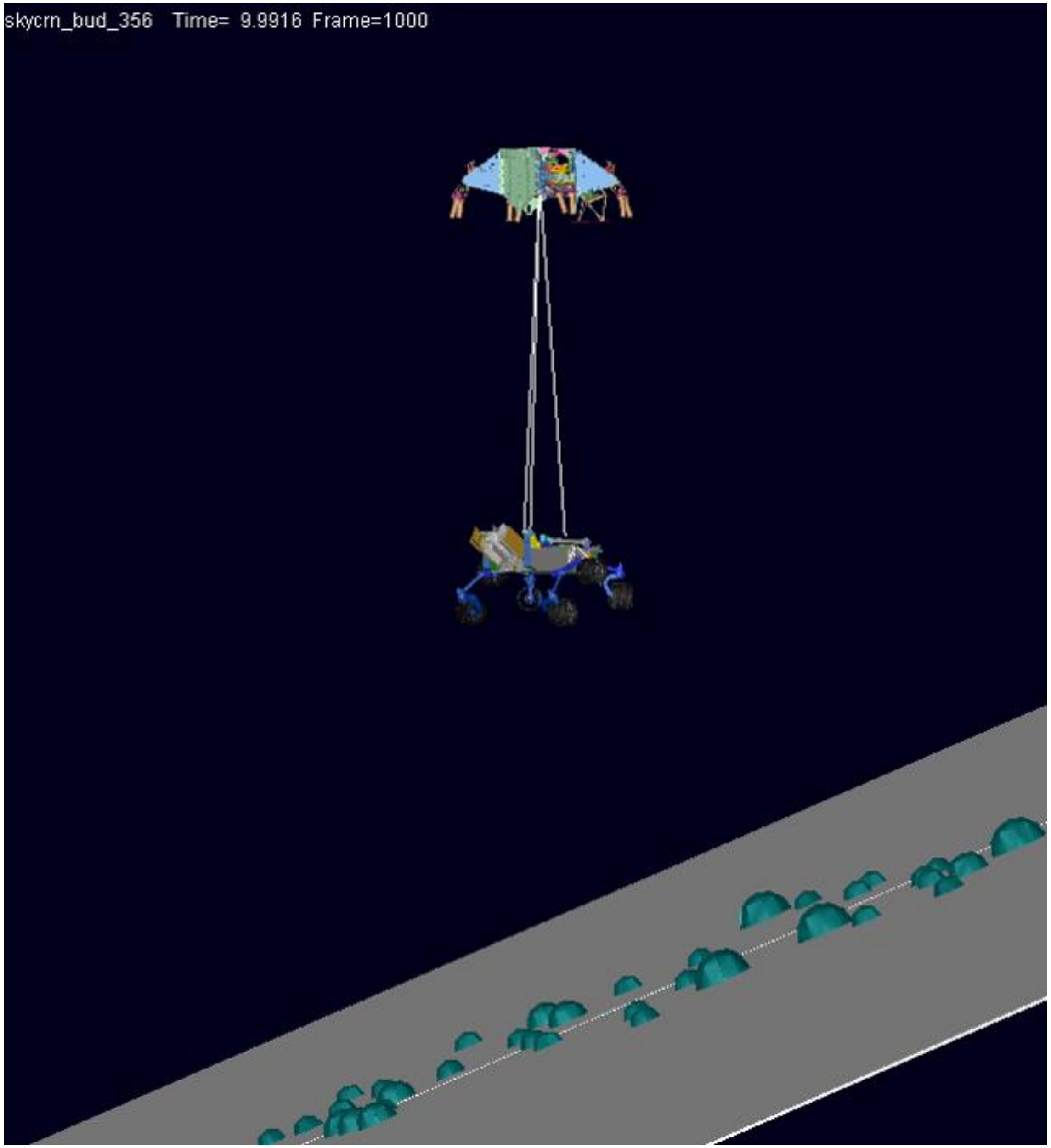
Towchdown Velocity:
- Vv = 0.75 m/sec
- Vh < 0.5 m/sec

- Robust to rocks
- Robust to local slopes
- Proven but hard rover egress
- Sensitive to winds
- Difficult to scale up

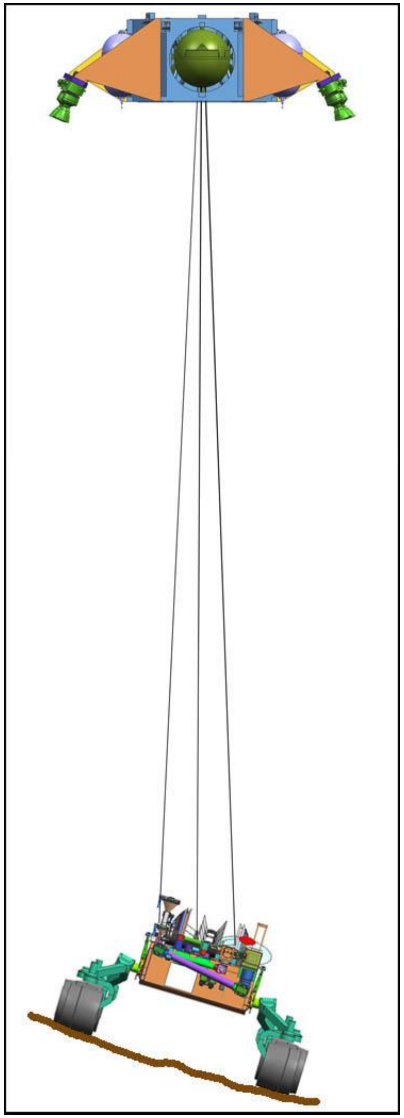
- Robust to winds
- Dedicated Touchdown Detection
- Sensitive to local slopes
- Sensitive to rocks
- Difficult rover egress

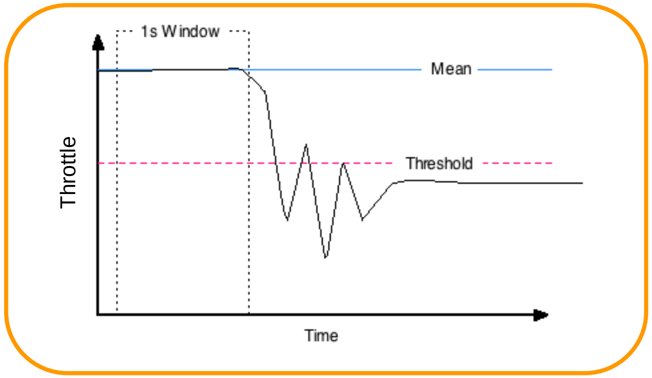
- Robust to winds
- Robust to local slopes
- Robust to rocks
- Simple touchdown detection
- No rover egress problem

# Continued Control Through Touchdown



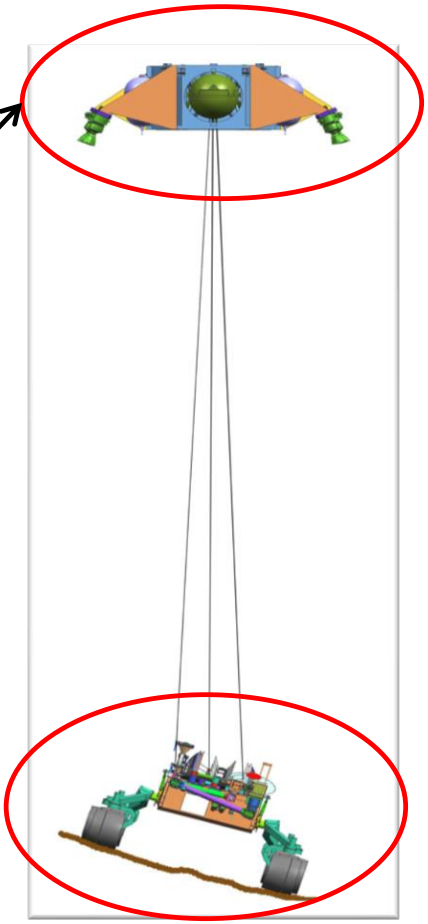
# SkyCrane Touchdown Detection



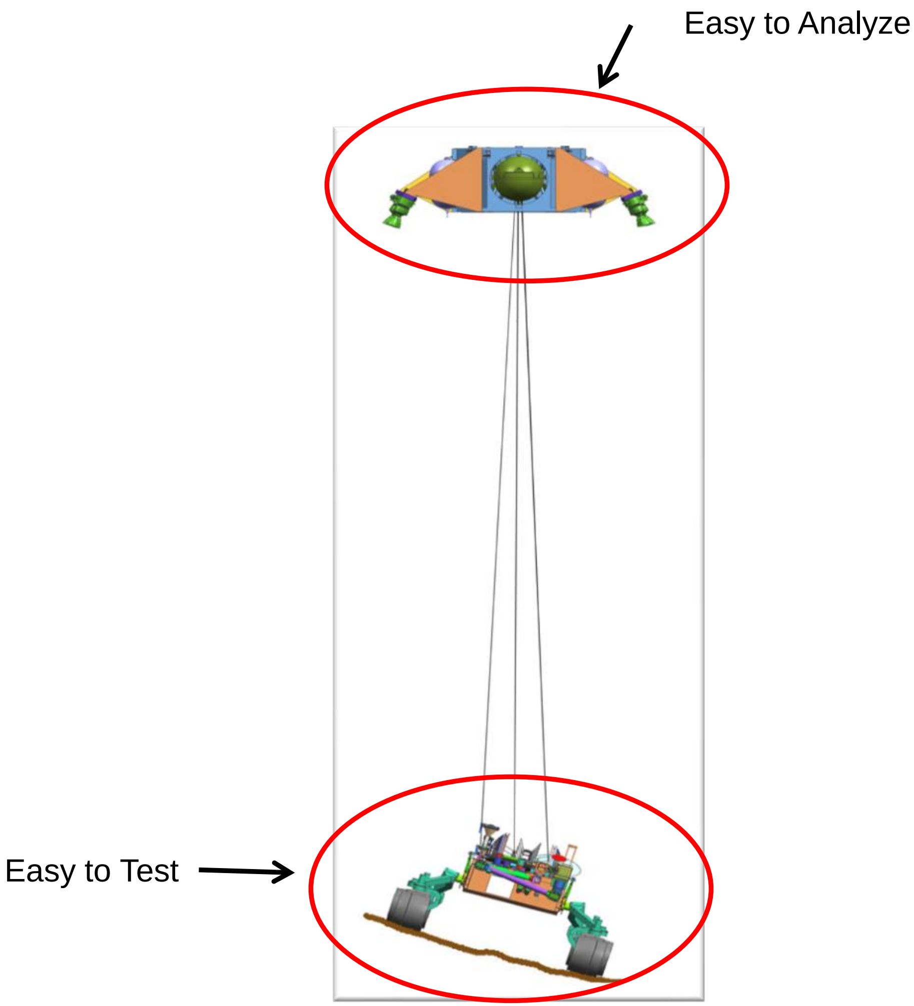


# Decoupled Delivery System from Payload

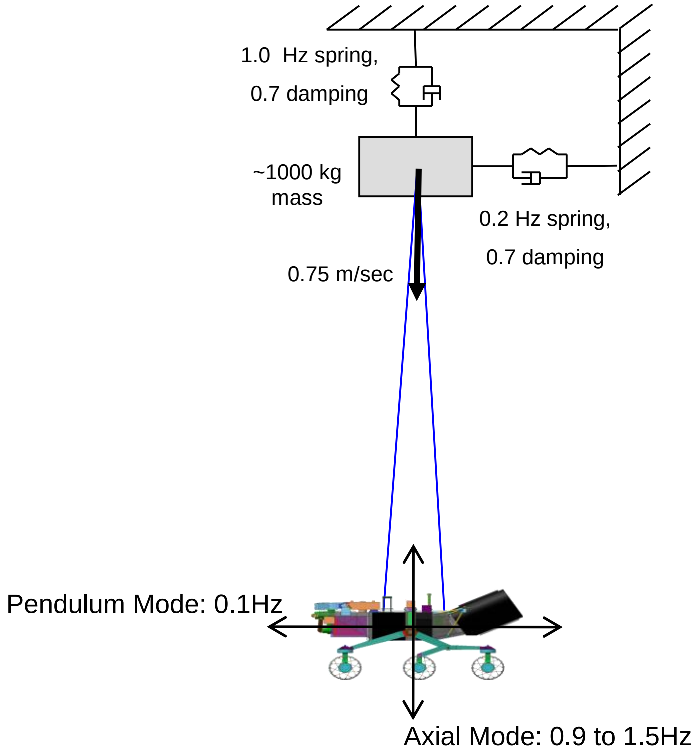
Decoupled Design, Development, & Testing

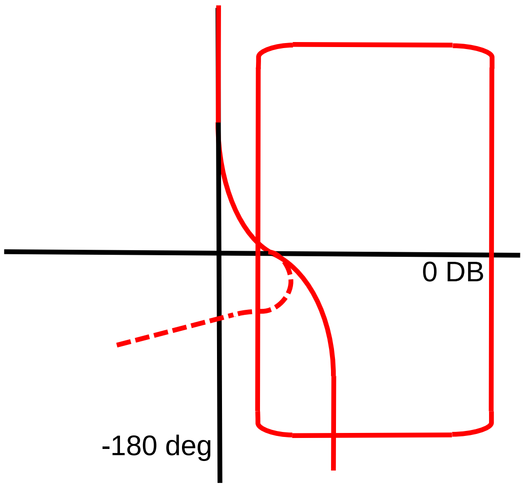


# Verification & Validation



# Phase Stabilization of SkyCrane Modes



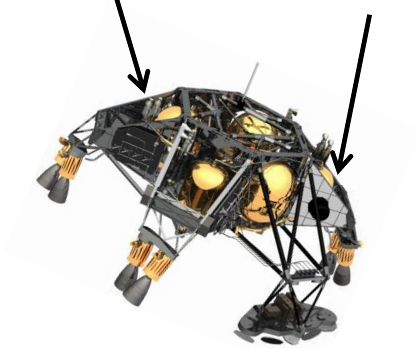
# Mini-TDT Test
## Lateral Mode

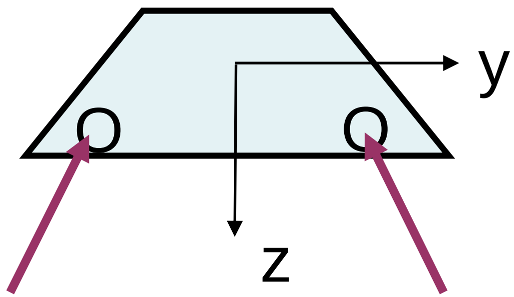
# Mini-TDT Test
## Axial Mode

# Fly-away

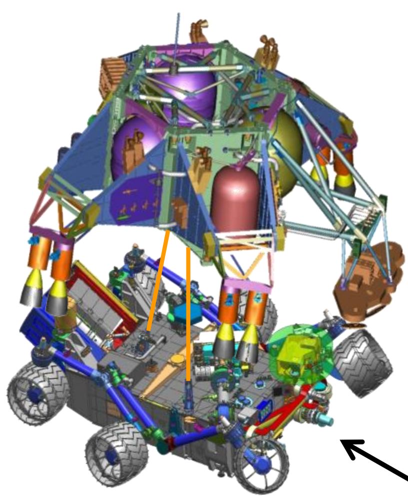
Throttle Valve
Motor Controller

IMU

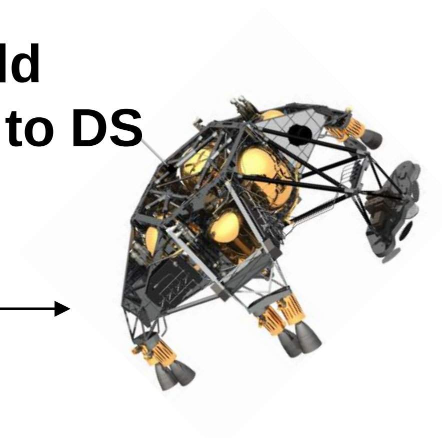





1) **Route IMU through Stage Motor Controller**
2) **Only Attitude Control**
3) **Rotate around body y-axis and hold**
4) **Implicit State Transfer from Rover to DS**
5) **Consume all the fuel**

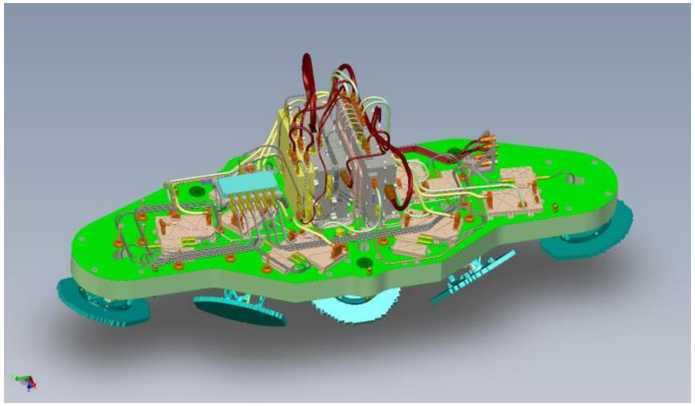


> 150 m



Rover Computer

# Key MSL GN&C/EDL Developments

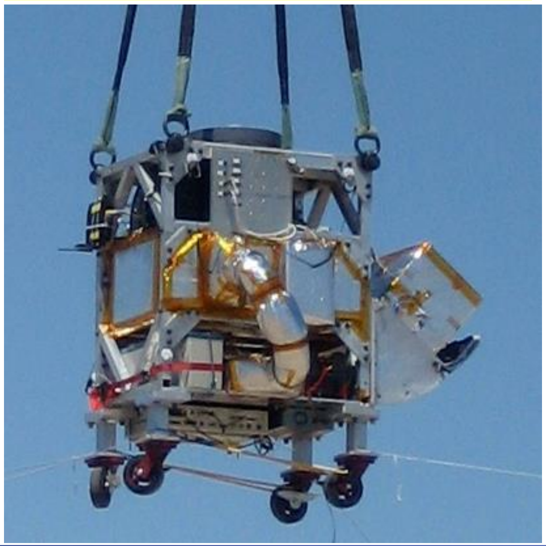


Terminal Descent Landing Sensor (TDS)

Mars Landing Engine (MLE)

# Field Test Venues

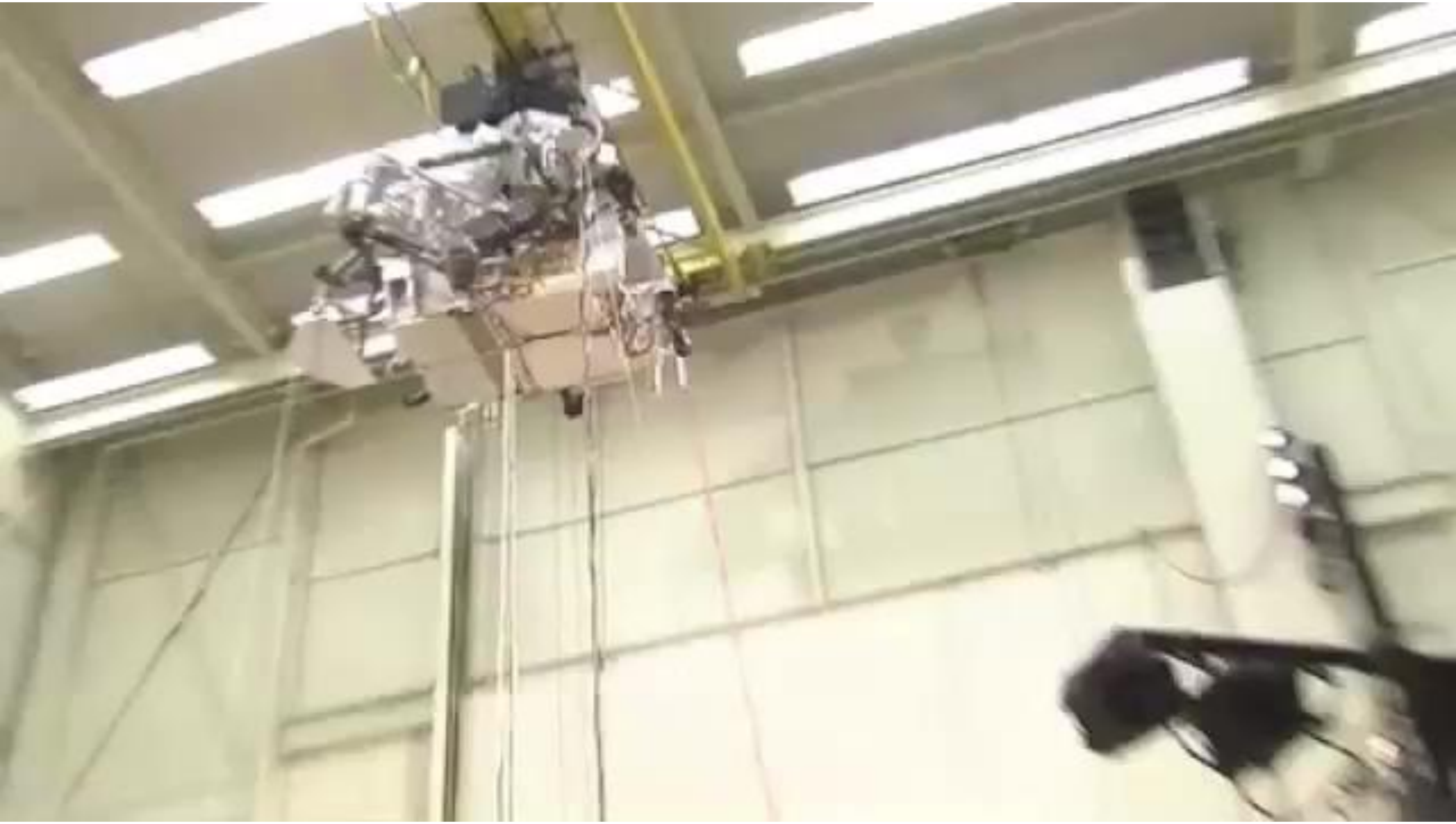
China Lake Echo Towers



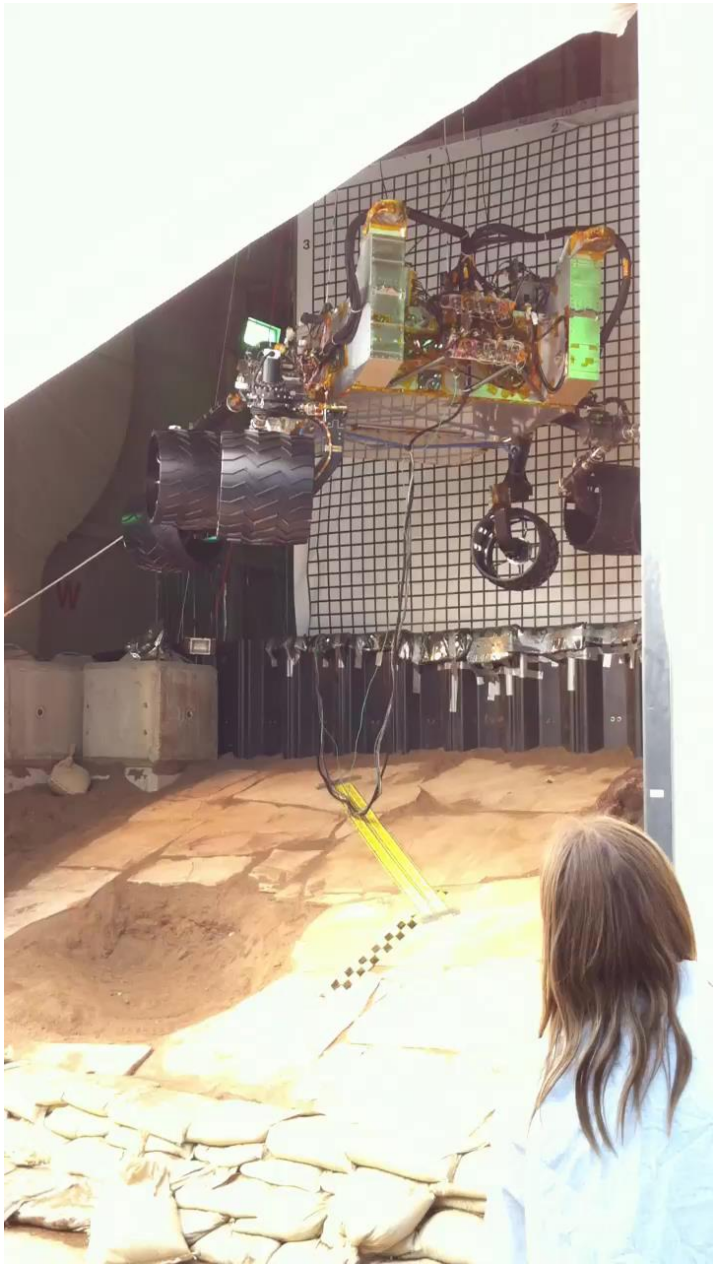

NASA Dryden Flight Research Center F/A-18

Eurocopter AS350 AStar Helicopter

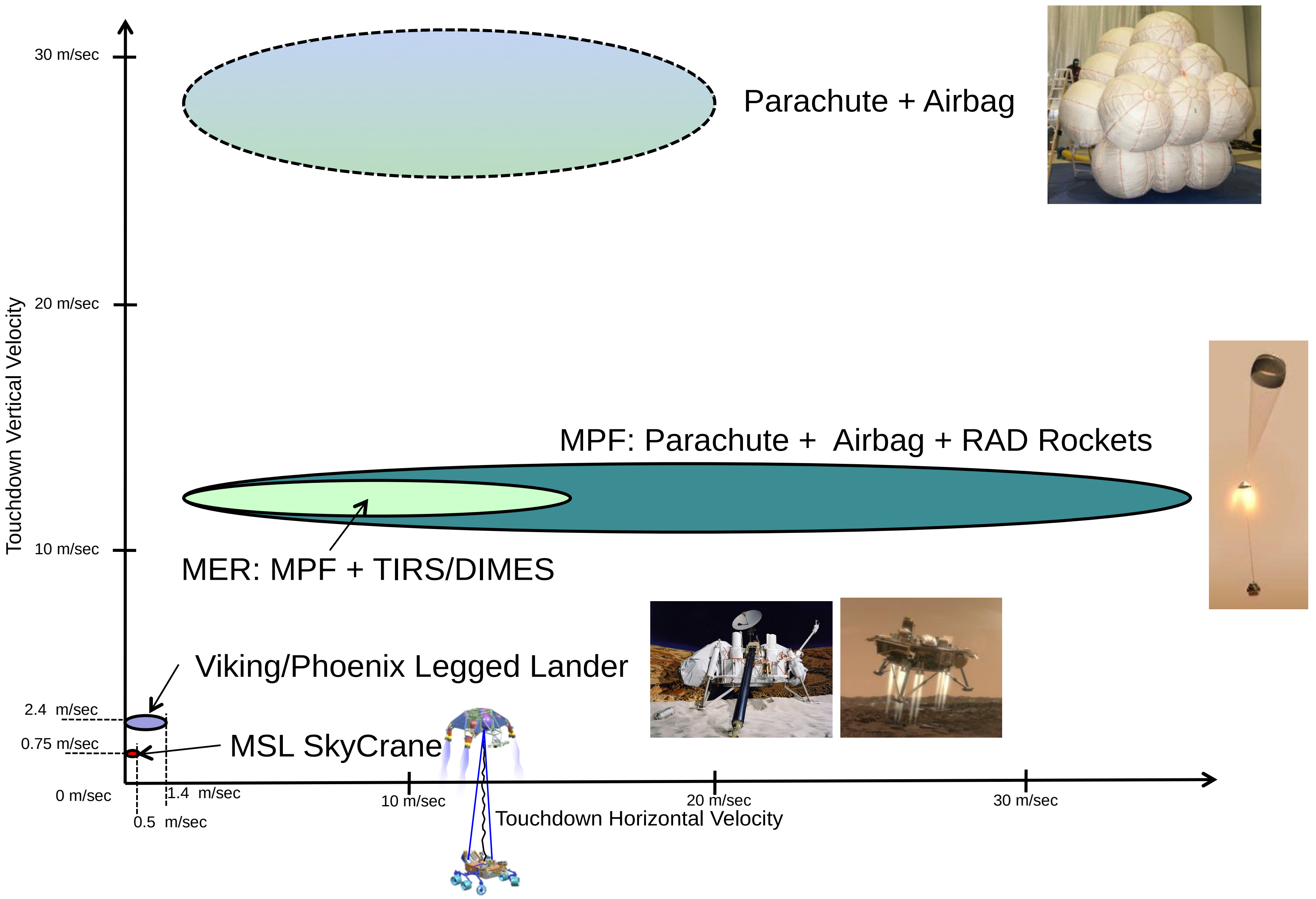
# Full Motion Test

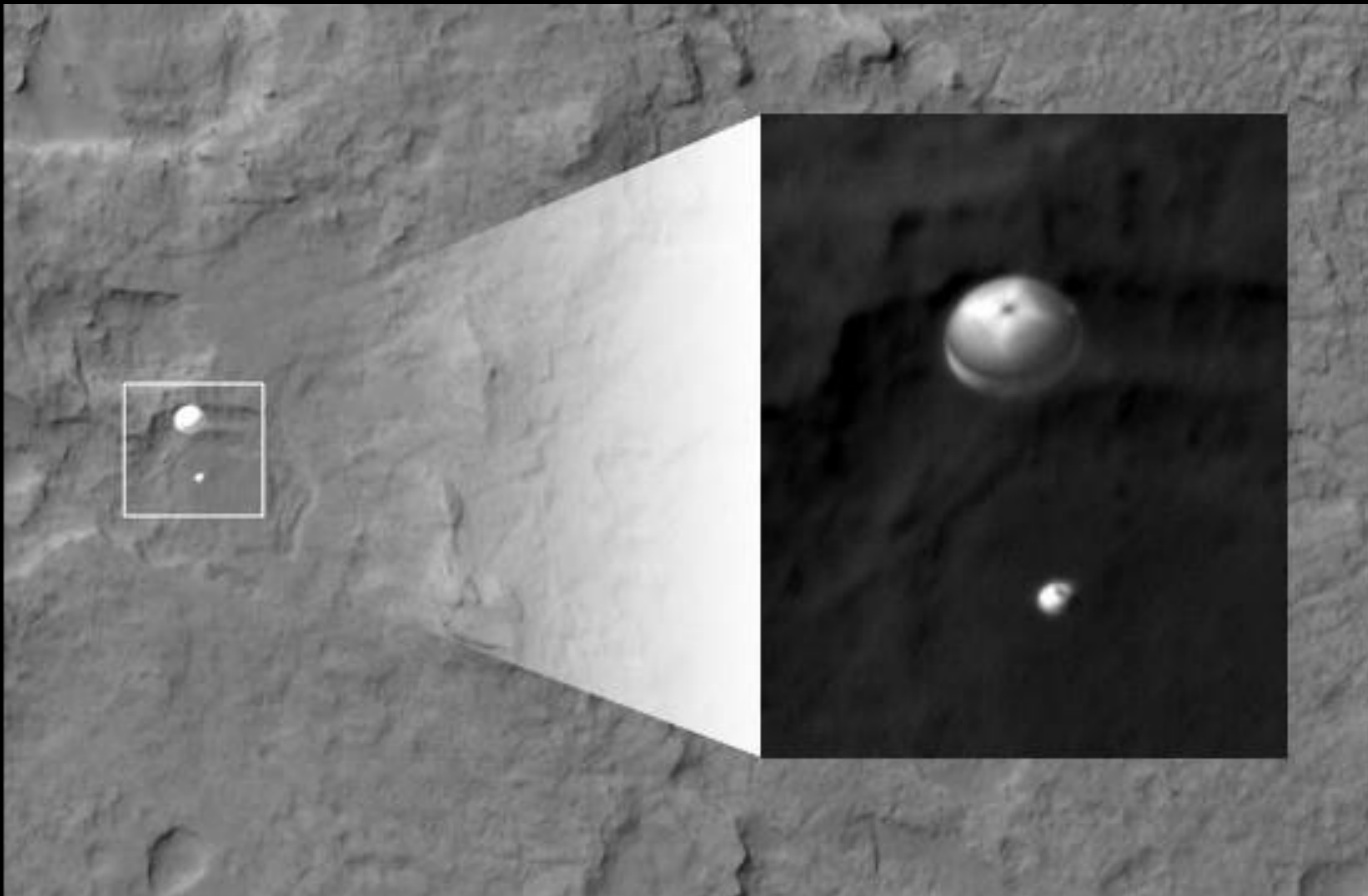


# Touchdown Test



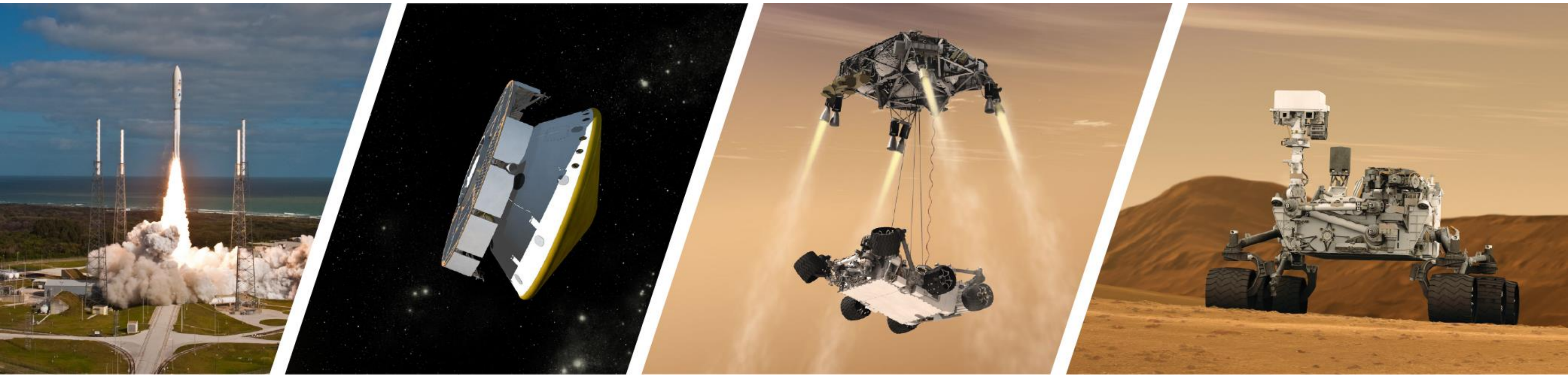
# History of Mars Touchdown Velocities





# Mount Sharp

# Mars 2020 Mission Overview



## LAUNCH

- MSL Class/Capability LV
- Period: Jul/Aug 2020

## CRUISE/APPROACH

- 7.5 month cruise
- Arrive Feb 2021

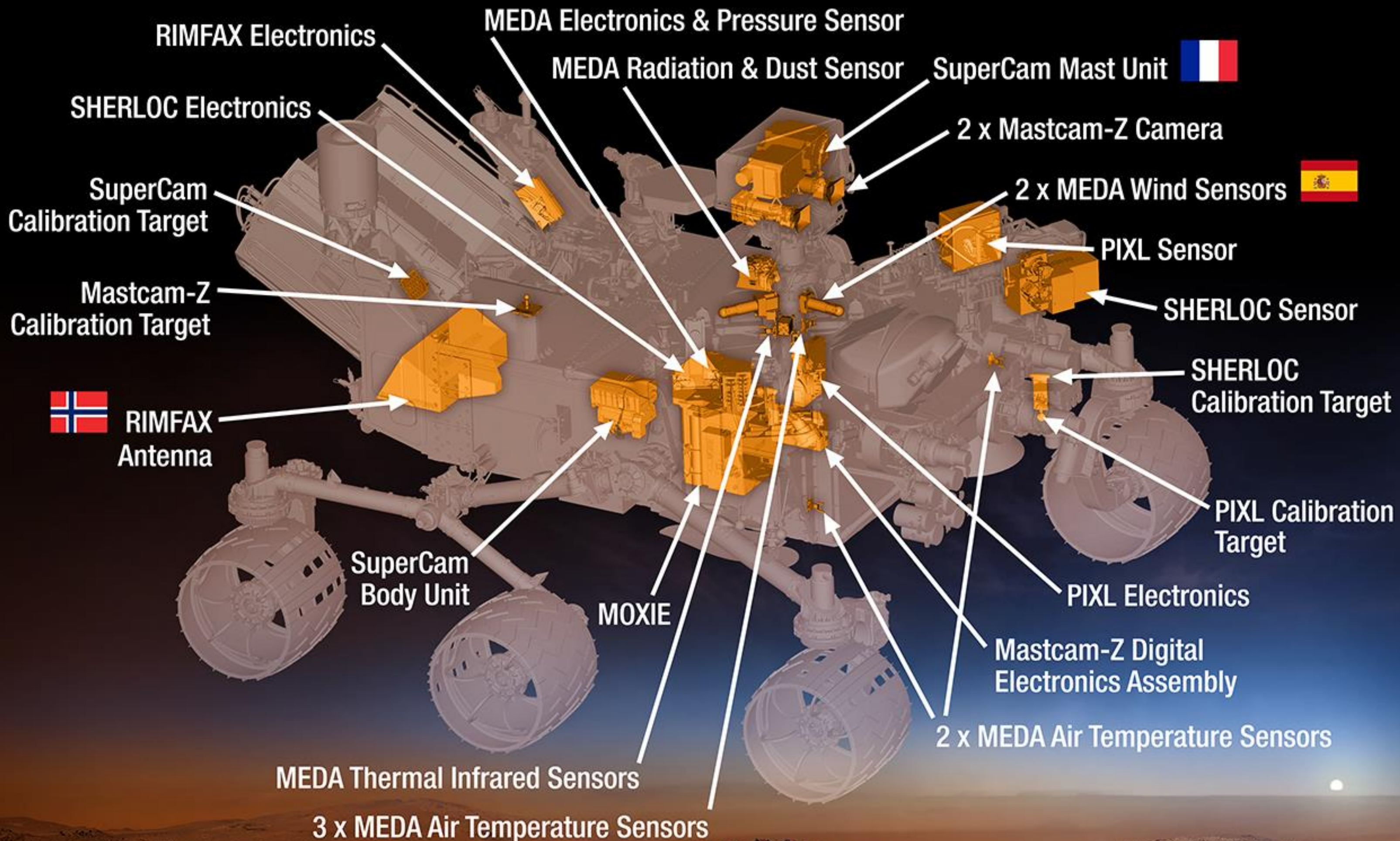
## ENTRY, DESCENT & LANDING

- MSL EDL system (Range Trigger baselined, Terrain Relative Navigation funded thru PDR): guided entry and powered descent/Sky Crane
- 16 x 14 km landing ellipse (range trigger baselined)
- Access to landing sites $\pm 30^{\circ}$ latitude,
  $\leq$ -0.5 km elevation
- Curiosity-class Rover

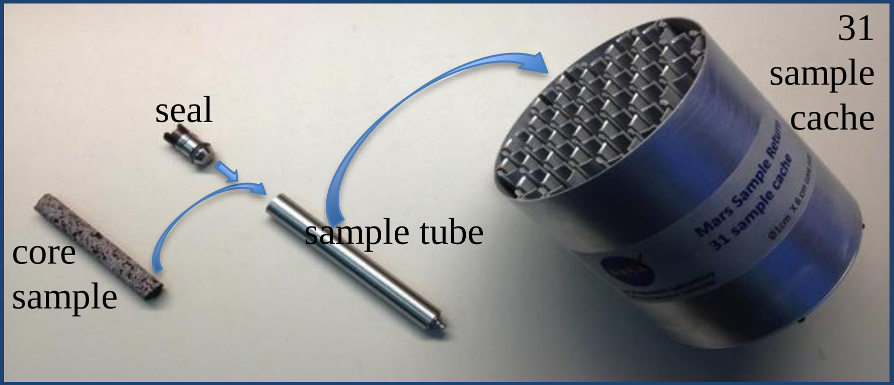
## SURFACE MISSION

- 20 km traverse distance capability
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

# Mars 2020 Instrument Payload Accommodated on Rover

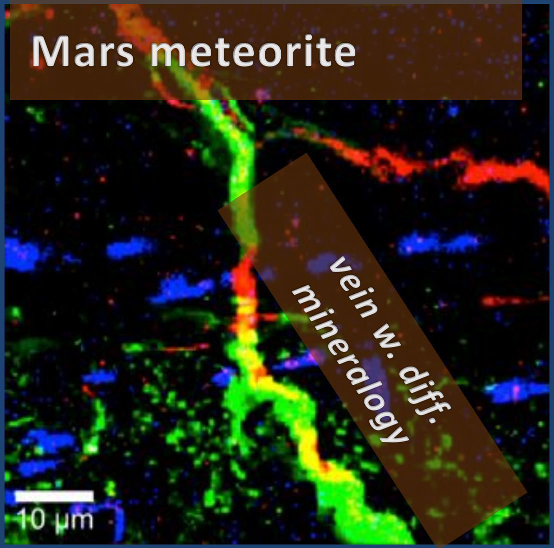


# The 2020 Mars Rover mission offers many important advances relative to MER and MSL:




The ability to collect compelling samples for potential future return

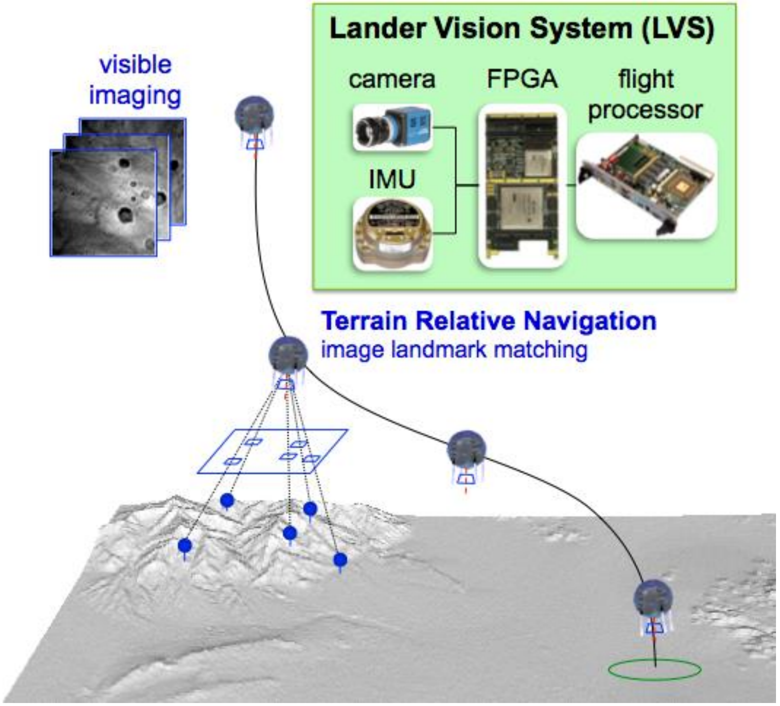
Payload designed to recognize potential biosignatures in outcrop

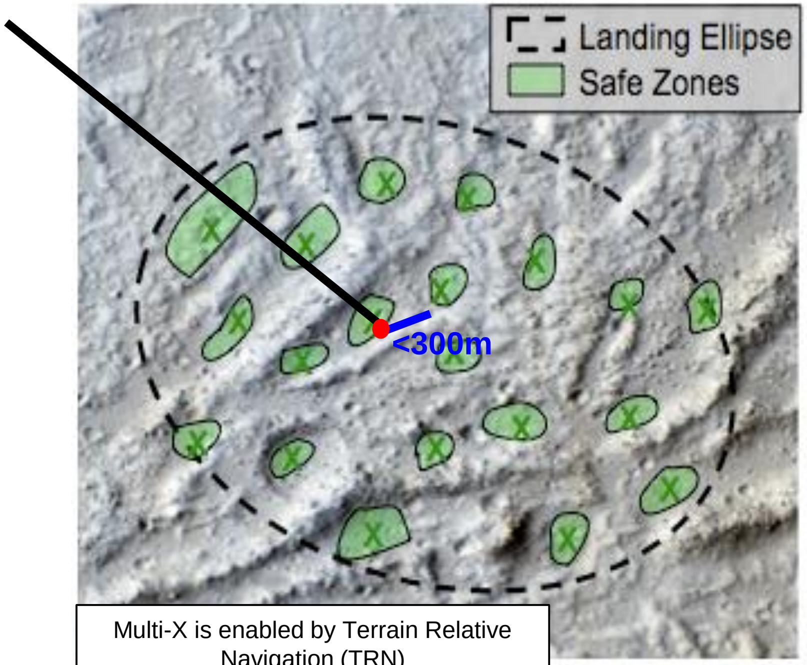



Measurements of fine-scale mineralogy, chemistry, and texture in outcrop (petrology)

Prepare for the future human exploration of Mars

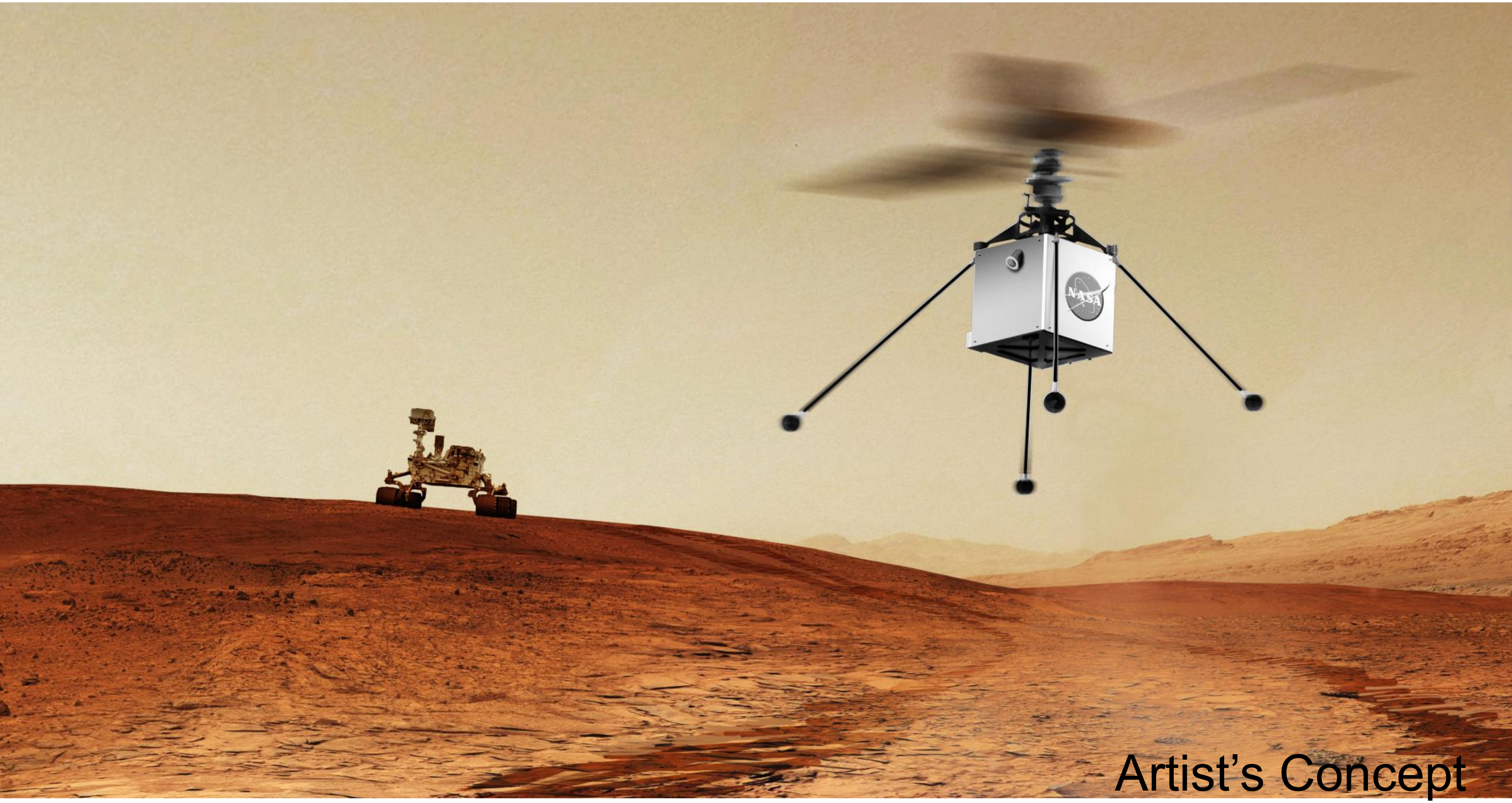
# Terrain Relative Navigation




Multi-X is enabled by Terrain Relative Navigation (TRN)

# Mars Helicopter for 2020?



# Conclusions

- Mars has provided a challenging destination that has resulted in the development of multiple EDL/GN&C architectures with different cost, risk, and performance

- Low cost solutions were successfully developed such as the MPF/MER airbag landers and the Phoenix soft-lander

- In order to meet the large improvement in landing accuracy and delivered payload, MSL enlisted GN&C early in the design cycle and developed the appropriate sensor and actuators required for the task
  - SkyCrane: Tightly integrated mechanical/GN&C design. GN&C is part of the Touchdown system

- Future improvements in EDL performance (Hazard Detection & Avoidance, Pinpoint Landing) will require the development of new, and maybe costly, GN&C sensors and actuators, and new ways of testing the full end-to-end system